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**ELECTROMYOGRAPHIC AND MECHANOMYOGRAPHIC TIME AND
FREQUENCY RESPONSES DURING FATIGUING, SUBMAXIMAL,
ISOKINETIC MUSCLE ACTIONS OF THE BICEPS BRACHII**

by

Ethan C. Hill

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Major: Nutrition and Health Sciences

Under the Supervision of Professor Terry J. Housh

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ELECTROMYOGRAPHIC AND MECHANOMYOGRAPHIC TIME AND
FREQUENCY RESPONSES DURING FATIGUING, SUBMAXIMAL, ISOKINETIC
MUSCLE ACTIONS OF THE BICEPS BRACHII

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University of Nebraska, 2016

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The purpose of the present investigation was to examine the time-course of changes in electromyographic (EMG) and mechanomyographic (MMG), time and frequency domain responses during repeated, submaximal, concentric, isokinetic, forearm flexion muscle actions. Twelve men (mean age \pm SD = 22.6 ± 2.2 yrs; body weight = 84.0 ± 8.3 kg; height = 178.6 ± 8.3 cm) performed 50 repeated, submaximal (65% of concentric peak torque), concentric muscle actions of the dominant forearm flexors on an isokinetic dynamometer at $60^\circ \cdot s^{-1}$. Surface EMG and MMG signals were simultaneously recorded from the biceps brachii muscle. Polynomial regression analyses (first, second, and third order) were used to examine the composite patterns of responses for EMG amplitude (AMP), EMG mean power frequency (MPF), MMG AMP, and MMG MPF across the fatiguing workout. The results indicated that across the fatiguing workout EMG AMP increased linearly ($r^2 = 0.961$), while EMG MPF decreased quadratically ($R^2 = 0.771$), and MMG AMP and MMG MPF decreased linearly ($r^2 = 0.747$ and $r^2 = 0.575$, respectively). The increase in EMG AMP, but decreases in EMG MPF and MMG MPF may have reflected the fatigue-induced recruitment of higher-threshold motor units with lower firing rates (as described by the Onion-Skin Scheme) due to the buildup of metabolic byproducts which interfere with contractile properties of the activated muscle fibers. Despite potential increases in motor unit recruitment, MMG AMP decreased

which may have been due to decreased muscle compliance. In addition to the Onion-Skin Scheme, it is also possible that the decrease in MMG MPF could be described by the Muscle Wisdom Theory which optimizes force production. Collectively, in the present study the increase in EMG AMP and decrease in MMG MPF may have reflected an increase in motor unit recruitment, but a decrease in motor unit firing rate which suggested that the maintenance in torque could be explained by both the Onion-Skin Scheme as well as the Muscle Wisdom Theory.

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Chapter I

INTRODUCTION

Surface electromyography (EMG) records and quantifies the action potentials that activate skeletal muscle fibers (5). The amplitude of the EMG signal is generated by the summation of the action potential trains from the active motor units and is influenced by the number of active motor units, their firing rates, and synchronization (5, 22). The power spectrum of the EMG signal is, in part, determined by average muscle fiber action potential conduction velocity (54) and the shape of the action potential waveforms (63). In addition, a number of anatomical, physiological, and non-physiological factors can affect the time and frequency domain parameters of the EMG signal including subcutaneous tissue layer, environmental noise, wave cancellation, and electrode placement (5, 33, 34, 48).

Mechanomyography (MMG) is a non-invasive technique that provides information related to muscle function that is unique from EMG. Gordon and Holbourn (42) described the MMG signal as the mechanical counterpart of motor unit activity as measured by EMG. MMG quantifies the lateral oscillations of activated muscle fibers that are generated by: (a) gross lateral movement of the muscle at the initiation of a contraction generated by the non-simultaneous activation of muscle fibers; (b) smaller subsequent lateral oscillations generated at the resonant frequency of the muscle; and (c) dimensional changes of the active fibers (65). It has been suggested that the amplitude of the MMG signal is related to motor unit recruitment and the frequency content of the MMG signal is related to motor unit firing rate (8, 65, 70). The MMG signal, however,

can also be influenced by muscle temperature, muscle stiffness, mass, the viscosity of the intracellular and extracellular fluids, and intramuscular fluid pressure (6, 65, 90).

Simultaneous measurements of EMG and MMG have been used to examine various aspects of muscle function including electromechanical and phonomechanical delay (77), muscle fiber type distribution patterns (73), muscle atrophy (32), and excitation-contraction coupling associated with muscle fatigue (90). Clinically, EMG and MMG measurements have been used in pediatric, adult, and geriatric populations to examine neuromuscular disorders such as myotonic dystrophy (67), mandipular disorders (53), low back pain (99), cerebral palsy (1), and to control prostheses (4).

A unique application of the simultaneous measurements of EMG and MMG is to examine the dissociation between the electrical and mechanical aspects of fatigue to examine motor unit activation strategies. With regard to fatigue, most studies have utilized isometric muscle actions (10, 11, 51, 58, 60, 82, 89, 101), but EMG and MMG measurements have also been applied to dynamic activities including concentric and eccentric muscle actions (2, 8, 9, 17, 18, 21, 29, 31, 43, 47, 71, 73, 74, 92, 98), and cycle ergometry (45, 75, 76, 85, 91). Fatiguing protocols involving concentric and eccentric muscle actions have generally included repeated, maximal muscle actions of the forearm flexors or leg extensors. Specifically, for the forearm flexors, Beck et al. (9) examined the effects of 50 repeated, maximal, concentric muscle actions at $180^{\circ}\cdot\text{s}^{-1}$ on the EMG and MMG amplitude and frequency responses from the biceps brachii and reported decreases in torque, MMG amplitude, EMG frequency, MMG frequency, but an increase in EMG amplitude. For the leg extensors, Camici et al. (18) examined the effects of 30

repeated, maximal, concentric muscle actions at $30^{\circ} \cdot s^{-1}$ and reported decreases in torque, EMG amplitude, EMG frequency, MMG amplitude, and MMG frequency from the vastus lateralis. In addition, Camic et al. (17) also examined the effects of 30 repeated, maximal, eccentric muscle actions at $30^{\circ} \cdot s^{-1}$ and reported decreases in torque, EMG frequency, and MMG frequency from the vastus lateralis, but no change in EMG amplitude and an increase in MMG amplitude. During maximal, isometric muscle actions, Bigland-Ritchie et al. (11) reported decreases in torque and EMG frequency from the biceps brachii following a sustained, forearm flexion muscle action, while Camic et al. (18) reported decreases in torque, EMG amplitude, EMG frequency, and MMG frequency, but no change in MMG AMP from the vastus lateralis following intermittent, leg extension muscle actions. Thus, assessment of EMG and MMG, time and frequency domain parameters during fatiguing tasks can provide information regarding the mode- and muscle-specific differences in motor unit activation strategies that modulate torque during isometric, concentric, and eccentric muscle actions.

Previous investigations (65, 82) have also suggested that there are intensity-related differences in motor unit activation strategies during fatiguing muscle actions. For example, Orizio (65) reported an increase, no change, and decreases in MMG amplitude from the biceps brachii during sustained, isometric, forearm flexion muscle actions at submaximal intensities of 20, 40, 60, and 80% of isometric maximal voluntary contraction (MVC), respectively. Furthermore, Seghers and Spaepen (82) reported a decrease and no change in EMG frequency from the biceps brachii during intermittent, isometric, forearm flexion muscle actions at submaximal intensities of 25 and 50% of isometric MVC, respectively. No previous investigations, however, have simultaneously

assessed EMG and MMG responses to examine the motor unit activation strategies during fatiguing, submaximal, dynamic muscle actions. Therefore, the purpose of the present investigation was to examine the time-course of changes in EMG and MMG, time and frequency domain responses during repeated, submaximal, concentric, isokinetic, forearm flexion muscle actions. Based on previous investigations (68, 82), we hypothesized that across the 50 submaximal, concentric muscle actions EMG amplitude would increase, while EMG frequency, MMG amplitude, and MMG frequency would decrease.

Chapter II

LITERATURE REVIEW

2.1 Factors that affect and influence the EMG and MMG responses

Orizio et al. (70)

The purpose of this investigation was to examine the integrated sound myogram (iSMG) and the integrated electromyogram (iEMG) responses of the biceps brachii (BB) during isometric ramp contractions. Seven healthy men (mean age \pm SD = 22.4 ± 1.3 yrs; body weight 68.8 ± 3.7 kg) volunteered to perform isometric ramp contractions from 10 – 100% of maximal voluntary contraction (MVC) in 10% increments. Bipolar surface electrodes (Ag-AgCl) were placed over the BB and a contact sensor transducer (Hewlett-Packard 21050A) was placed between the bipolar electrode arrangement. The results indicated that iEMG tracked the increases in MVC up to 100%, while iSMG tracked the increases in MVC up to 80% and then decreased. Thus, firing rate and motor unit recruitment affected the iSMG and iEMG similarly up to 80% MVC. The authors concluded that iSMG may be affected by intramuscular pressure, but together, iEMG and iSMG may be used to differentiate the motor unit activation strategies during non-fatiguing isometric, forearm flexion muscle actions.

Yeung et al. (98)

The purpose of this investigation was to examine the neuromuscular responses of the vastus medialis following 30 repeated, maximal, leg extension muscle actions. Nineteen men (mean age = 26.5 yrs) volunteered to randomly perform 3 maximal voluntary contractions (MVC) before and after performing 30 repeated, maximal,

isometric, leg extension muscle actions. Total reaction time (TRT), time to the onset of force, premotor time (PMT), and electromechanical delay (EMD) were measured. The results indicated decreases in peak force, an increase in EMG AMP and EMD, a decrease in PMT, and no changes in EMG MPF or TRT. The authors suggested that the non-significant change in TRT was related to a balance between a lengthened EMD interval (which increases TRT) and a faster PMT response (which decreases TRT).

Zwarts et al. (101)

This investigation examined the effects of blood flow on electromyographic muscle fiber conduction velocity (EMG MFCV) and EMG median power spectrum (EMG MPS) during a sustained isometric contraction of the biceps brachii (BB). Three subjects (mean age = 35 yrs) performed a sustained isometric contraction at 40% of their maximal voluntary contraction (MVC) with and without ischemia. Ischemia was applied using a blood pressure cuff and fatigue was defined as the inability to maintain 40% of MVC. The results indicated a linear decrease between EMG MFCV and EMG MPS during the sustained contraction. During recovery, however, EMG MPS was restored faster than EMG MFCV without ischemia, while with ischemia, EMG MFCV did not recover and only partial recovery was seen in EMG MPS. The authors concluded that a shift in EMG MPS to lower frequencies cannot be entirely explained by the changes in EMG MFCV. Therefore, the authors suggested that EMG MPF should be used cautiously when estimating EMG MFCV and to further examine the relationship between EMG MFCV and EMG MPF.

Kouzaki et al. (51)

This study examined the effects of blood flow on the integrated electromyographic (iEMG) and integrated mechanomyographic (iMMG) responses to repeated, maximal, isometric muscle actions. Seven men (mean age \pm SD = 24.4 ± 1.4 yrs; body weight 68.8 ± 10.4 kg) volunteered to perform 50, repeated, maximal, isometric, leg extension muscle actions. Bipolar surface electrodes and accelerometers were placed on the rectus femoris, vastus lateralis, and vastus medialis muscles. The results indicated that maximal voluntary isometric contraction (MVIC) and iEMG decreased similarly throughout the fatiguing workout. The iMMG, however, declined uniquely for each muscle, most notably for the rectus femoris. The authors attributed the differences in the iMMG responses to muscle architecture and to morphological differences, whereby the rectus femoris has a greater proportion of fast-twitch motor units. Collectively, the authors suggested that iEMG may track the fatigue-related decreases in torque, while iMMG may be used to differentiate muscle characteristics.

Sejersted et al. (83)

This study examined the effects of isometric force and intramuscular pressure on electromyographic (EMG) and mechanomyographic (MMG) responses during isometric, leg extension muscle actions. Seven adults (mean age = 55 yrs; body weight 64 kg) performed isometric ramp contractions (0 – 60% of maximal voluntary contraction, MVC) and sustained isometric contractions at 10, 20, and 40% of MVC. Pressure was artificially applied using a blood pressure cuff, while intramuscular pressure was measured by a transducer-tipped catheter. A bipolar surface electrode (Ag-AgCl)

arrangement and an accelerometer were placed on the vastus lateralis muscle. The results indicated a linear relationship between external pressure and intramuscular pressure, but an inverse relationship between pressure and EMG and MMG root-mean-squared (EMG RMS and MMG RMS) values. MMG RMS, however, was less affected by increases in intramuscular pressure. Therefore, the authors concluded that intramuscular pressure may not attenuate the MMG RMS; rather, the observed decreases in MMG RMS may be the result of a fusion-like state within the muscle fibers due to high motor unit firing rate.

Beck et al. (8)

The purpose of this study was to examine the effects of submaximal (20 – 80% of maximal voluntary contraction, MVC) and maximal isokinetic and isometric muscle actions on mechanomyographic amplitude (MMG AMP) and MMG mean power frequency (MMG MPF). Five men (mean age \pm SD = 22.0 \pm 1.9 yrs; body weight 79.0 \pm 5.6 kg) and 5 women (mean age \pm SD = 21.2 \pm 1.6 yrs; body weight 63.9 \pm 7.6 kg) performed maximal and submaximal concentric (at 30°·s⁻¹) and isometric muscle actions of the forearm flexors on a calibrated Cybex II isokinetic dynamometer. A piezoelectric crystal contact sensor (Hewlett-Packard 21050A) was placed over the biceps brachii muscle. The results indicated a linear increase in MMG AMP and force during the concentric ($r^2 = 0.982$) and isometric ($r^2 = 0.956$) muscle actions. The MMG MPF responses, however, were best-fit by cubic models during the concentric ($R^2 = 0.786$) and isometric ($R^2 = 0.940$) muscle actions. This study provided insight into the motor control strategies that modulate concentric and isometric torque production. For example, the increase in MMG AMP without a change in MMG MPF during the concentric muscle

actions indirectly suggested that concentric torque was modulated by motor unit recruitment alone, while the increase in MMG AMP with a concomitant increase in MMG MPF during the isometric muscle actions indirectly suggested that torque was modulated by both motor unit recruitment and firing rate.

Orizio et al. (68)

This investigation analyzed the mechanomyographic (MMG) time and frequency responses during an isometric ramp contraction in non-fatigued and fatigued muscle. Ten subjects (20 – 30 yrs) volunteered to perform isometric ramp contractions (0 – 90% maximal voluntary contraction, MVC) of the biceps brachii (BB). Fatigue was induced by repeated isometric contractions at 50% of MVC until the subjects could no longer maintain the required force output. A bipolar surface electrode arrangement was placed on the BB and an accelerometer (Entran EGAS FT 10) was placed between the bipolar electrode arrangement. The results of the study indicated that electromyographic root-mean-squared (EMG RMS) increased with force in both non-fatigued and fatigued muscle. Similarly, EMG mean frequency (EMG MF) and MMG MF increased with force, but was lower in the fatigued muscle. MMG RMS and MMG MF responded differently in the non-fatigued and fatigued muscle. Specifically, in non-fatigued muscle MMG RMS increased from 20 – 65% of MVC and declined from 65 – 85% of MVC, while in fatigued muscle MMG RMS decreased from the start of contraction. Furthermore, MMG MF increased with force in both conditions, but to a lesser extent in fatigued muscle. The increases in MMG RMS in non-fatigued muscle were attributed to an increase in motor unit recruitment. The lack of change in MMG RMS in the fatigued

muscle was attributed to the inability to recruit already fatigued type II motor units. The increase in MMG MF in both conditions, however, indirectly suggested that motor unit firing rate modulated the final increases in force production. In addition, increased firing rate may have also created a fusion-like state within the muscle which resulted in the observed decrease in MMG RMS.

McHugh et al. (61)

The purpose of this study was to compare the electromyographic (EMG) frequency responses during concentric and eccentric muscle actions. Ten men (mean age \pm SD = 31.0 ± 7.2 yrs; body weight 88.6 ± 6.6 kg; height 179 ± 6.0 cm) volunteered to perform eccentric and concentric leg extension muscle actions at $60^\circ \cdot s^{-1}$ at 25, 50, 75, and 100% of maximal voluntary contraction on a calibrated isokinetic dynamometer (Biodex System 2). Bipolar surface electrodes (Ag-AgCl) were placed on the vastus lateralis (VL), vastus medialis (VM), and rectus femoris (RF) muscles. The results indicated that peak torque and EMG frequency were greater during the eccentric than concentric muscle actions. EMG frequency, however, increased during the concentric muscle actions, but remained stable during the eccentric muscle actions and was greatest from the RF muscle. EMG root-mean-squared (EMG RMS) increased with contraction intensity during the concentric and eccentric muscle actions, although EMG RMS was greater during the concentric muscle actions. The authors concluded that the increases in EMG frequency were related to the recruitment of higher-threshold motor units (fast-twitch). That is, the authors suggested that the RF had the greatest proportion of fast-twitch motor units and, thus, resulted in a greater increase in EMG frequency. Furthermore, the motor unit

activation strategies associated with concentric and eccentric muscle actions were different and the authors suggested that eccentric muscle actions may preferentially recruit fast-twitch motor units, while concentric muscle actions recruit motor units according to the size principle.

2.2 Factors that affect muscle fatigue

Bigland-Ritchie et al. (10)

The purpose of this investigation was to examine the central and peripheral factors associated with repeated, submaximal, isometric muscle actions. Ten adults volunteered to perform intermittent, isometric muscle actions of the adductor pollicis muscle at 50% of maximal voluntary contraction (MVC) until force could not be maintained within 5% of target force. Periodically, a fatigue test was administered which included an MVC or superimposed twitch. The results indicated that at endurance limit, MVC force declined by 50% and superimposed twitches decreased across time until disappearing altogether. The authors concluded that central fatigue was not a contributing factor to fatigue as evidenced by the diminishing superimposed twitches. Instead, fatigue was related to peripheral factors which may have led to excitation-contraction coupling failure.

Søgaard et al. (89)

The purpose of this investigation was to examine the effects of proprioceptive versus visual feedback during submaximal, isometric muscle actions. Six men (mean age = 28.8 yrs; body weight 79.3 kg) volunteered to perform 30 minutes of intermittent (6 s on, 4 s off) isometric, forearm flexion muscle actions at 30% of maximal voluntary contraction (MVC) with visual or proprioceptive feedback, and at 10% of MVC with

visual feedback only. To examine the effects of visual and proprioceptive fatigue, prior to exercise, as well as 10 and 30 minutes after exercise, isometric maximal voluntary contractions (MVC) were performed at 5% of MVC, 80% of MVC, and 100% of MVC. A bipolar electrode arrangement was placed on the belly of the biceps brachii and a piezoelectric uniaxial accelerometer was placed one-third the distance between the acromion and the fossa cubit. The results indicated decreases in MVC torque during all fatigue tests, and most notably during the 30% proprioceptive protocol. Furthermore, there were increases in EMG AMP and MMG AMP, but no changes in EMG MPF or MMG MPF. In addition, proprioceptive feedback was more difficult than visual feedback as evidenced by ratings of perceived exertion, force fluctuation, and a greater increase in EMG AMP. These findings indicated that proprioceptive feedback was more difficult than visual feedback and caused greater fatigue during submaximal, isometric muscle actions.

Sjogaard et al. (86)

The purpose of this study was to examine the effects of a sustained maximal voluntary contraction (MVC) on blood flow, blood pressure, heart rate, rating of perceiving exertion, electromyographic amplitude (EMG AMP), and intramuscular pressure. Seven men (mean age = 27 yrs; body weight 77 kg) volunteered to perform a sustained, isometric, leg extension muscle actions for 60-min at 5% of MVC. Blood flow was measured using catheters inserted into the femoral vein, while Teflon catheters were placed in the vastus medialis to measure intramuscular pressure. Bipolar surface electrodes (Ag-AgCl) were placed on the vastus lateralis and rectus femoris muscle. The

results indicated that intramuscular pressure and blood flow were unaffected during the sustained MVC, although fluctuations in pressure were observed. Throughout the sustained MVC, ratings of perceived exertion increased, while post MVC torque decreased. The authors concluded that alternating recruitment may have permitted heterogeneously distribution of blood flow within the working muscle and, therefore, delayed the onset of muscle fatigue.

Babault et al. (2)

The purpose of this investigation was to examine the central and peripheral factors that mediate fatigue during concentric and isometric muscle actions. Nine men (mean age \pm SD = 21.2 ± 1.1 yrs; body weight 71.0 ± 6.5 kg) volunteered to perform 3 bouts of 30 repeated, maximal, concentric, leg extension muscle actions at $60^\circ \cdot s^{-1}$ and a sustained maximal, isometric leg extension muscle action on a calibrated Biodex 3 isokinetic dynamometer. A bipolar surface electrode (Ag-AgCl) arrangement was placed on the vastus lateralis (VL) muscle. A high-voltage stimulator (Digitimer DS7) was used to assess voluntary activation which was calculated from the superimposed twitch to the resting twitch. The results indicated decreases in torque for both concentric and isometric muscle actions. Similarly, voluntary activation decreased for both contraction types, but decreased to a greater extent during the isometric muscle actions. Electromyographic root-mean-squared (EMG RMS) did not change throughout the concentric muscle actions, but decreased during the isometric muscle actions. The results indicated that fatigue from isometric contractions occurs centrally (as evidenced by the decrease in EMG RMS), while fatigue starts peripherally during concentric muscle actions (as

evidenced by the lack of change in EMG RMS). The differences observed during the concentric and isometric muscle actions may also be mediated by other mechanisms such as recurrent inhibition, presynaptic inhibition of Ia afferents, stretch-reflex, and Golgi tendinous apparatus.

Fortune and Lowery (35)

The purpose of this study was to examine the effects of extracellular potassium concentration and the temperature-related effects on muscle fiber action potential conduction velocity and membrane excitability. This study created a model-based representation of ionic channels allowing for the manipulation of potassium, sodium, chloride, and the sodium-potassium pump in vitro environment. The model was manipulated to simulate actual processes within working skeletal muscle. The results indicated that increased potassium concentration resulted in a broadening of peak to peak amplitude, as well as, a decrease in muscle fiber action potential conduction velocity. Increases in temperature, however, decreased transmembrane resting potential and, therefore, was more sensitive to sodium concentrations. During repetitive stimulation, action potential conduction velocity slowed due to an accumulation of potassium in the transverse tubule and interstitial space. These results suggested that potassium may be a large contributor to the slowing of motor unit action potential conduction velocity as indicated by the decreases in conduction velocity and the associated broadening of action potentials with increases in potassium in both the transverse tubules and interstitial space.

This study examined the relationship between intramuscular pressure and delayed onset muscle soreness. Eight men (age 21 – 40 yrs; mean body weight 67 – 85 kg; height 175 – 184 cm) performed maximal concentric and eccentric muscle actions at $60^{\circ} \cdot s^{-1}$ until exhaustion (as determined by the subject). Intramuscular pressure was measured from the vastus lateralis muscle. The results of this study indicated that intramuscular pressure was not a precursor to delayed onset muscle soreness. In addition, intramuscular pressure was not different between concentric and eccentric conditions and did not change throughout the repetitions. The intramuscular to torque coefficient (pressure divided by torque), however, was significantly higher during the concentric muscle actions, but increased across repetitions regardless of muscle action. In addition, peak torque was greater (191 vs. 166 Nm) during the eccentric muscle actions, but decreased across repetitions regardless of muscle action. Muscle soreness occurred on the second day after the eccentric exercise and was most prominent in the mid portion of the vastus lateralis muscle, although no changes were observed for joint angle peak torque during the eccentric or concentric muscle actions. The authors concluded that intramuscular pressure was not associated with delayed onset muscle soreness and that intramuscular pressure was similar for both types of muscle actions. Furthermore, joint angle peak torque was not affected by either muscle action or delayed onset muscle soreness. The greater intramuscular to torque coefficient during the concentric muscle actions was attributed to the difference in peak torque between the concentric and eccentric muscle actions.

This investigation examined the central and peripheral factors associated with muscle fatigue during concentric and eccentric actions. Eight men and 2 women (age 22 – 44 yrs; mean body weight \pm SD = 70.2 ± 8.9 kg; height 176.7 ± 7.9 cm) performed 5 sets of 30 repeated, maximal, concentric and eccentric dorsi flexion muscle actions at $50^\circ \cdot s^{-1}$. A bipolar surface electrode (silver disks) arrangement was placed over the tibialis anterior, while torque was measured using a linear potentiometer and strain gauge transducer (sensitivity: 0.018 V/Nm; linear range: 0 – 200 Nm). Electrical stimulation was delivered to the peroneal nerve and post-activation potentiation (PAP) was calculated from the twitch before and after the maximal voluntary isometric contraction (MVIC). The results indicated that torque was greater during the eccentric than the concentric muscle actions, but decreased across both muscle actions. Voluntary activation (electromyographic amplitude, EMG AMP) was less during the eccentric muscle actions and remained unchanged throughout the fatigue tests, while PAP decreased by 18.4 and 8.6% for the eccentric and concentric muscle actions, respectively. The torque to EMG ratio was greater during the eccentric muscle actions and remained stable throughout each set, but decreased during the concentric muscle actions. Collectively, the decrease in torque without a significant change in M-wave amplitude suggested that neuromuscular transmission failure did not occur. The progressive lengthening of the M-wave during the concentric muscle actions, however, was attributed to high-frequency fatigue from fatigue-induced alterations in excitation-contraction coupling. The non-significant change in M-wave amplitude and recovery of PAP suggested that the decreases torque

were the result of increased intracellular calcium which adversely affected excitation-contraction coupling.

2.3 Factors that affect muscle function, analysis, and interpretation

Rudroff et al. (80)

This investigation compared the electromyographic (EMG) responses of surface versus indwelling electrodes during a submaximal test to exhaustion. Ten men (mean age \pm SD = 25 ± 6 yrs; body weight 72 ± 5 kg; height 176 ± 9) volunteered to perform a submaximal (20% of maximal voluntary contraction), sustained, isometric, forearm flexion muscle action to exhaustion. Bipolar surface electrodes (Ag-AgCl) were placed over the brachioradialis and the long and short heads of the biceps brachii muscle according to the recommendations of Merletti et al. (62). Steel wire electrodes (California Fine Wire) were inserted between each bipolar surface arrangement, while muscle thickness and electrode depth were measured using ultrasound. The results indicated that EMG amplitude increased for the surface and intramuscular electrodes, although the rate of increase was greater for the surface electrodes. The authors concluded that the surface electrodes were more representative of time to task failure. Furthermore, the rates of increase for both surface and intramuscular EMG were not related to thickness of subcutaneous tissue for the long head of the biceps brachii or the brachioradialis. Finally, the authors concluded that the different rates of increase for surface and intramuscular EMG may be related to changes in shape of the volume conductor, thickness of subcutaneous tissue, crosstalk, and conduciveness of the tissues.

The purpose of this study was to examine the effects of motor unit firing rates during voluntary and stimulated contractions. Three men volunteered to perform sustained isometric muscle actions of the adductor pollicis muscle. Force was measured using a transducer (RCA 5734 mechanoelectric transducer valve) and muscle temperature was determined using a needle thermocouple inserted into the dorsal side of the adductor pollicis. To examine the effects of temperature, subjects completed the task in a hot and cold environment. Surface electrodes (lint-covered silver ring) were placed over the first metacarpal and on the ring finger, while muscle stimulation was administered to the ulnar nerve with a cathode using an isolating transducer. To block voluntary activation, the median nerve was blocked using 1% iodocaine hydrochloride with norepinephrine. The results of this study indicated that optimal firing rate of the muscle declines during sustained voluntary and stimulated contractions. In addition, during prolonged contractions, the firing rate of single motor units decline in both voluntary and artificially stimulated experiments, while the effect of temperature was trivial in both voluntary and artificial experiments. The authors theorized that the slowing of motor unit firing rate was related to activation failure and/or the muscle optimizing force production. For example, repetitive excitation may result in activation failure and, therefore, slowing the rate of discharge may prevent activation failure. Secondly, during a sustained contraction the innervation rate decreases such that reduced excitation is needed to produce similar force. Together, these mechanisms work conjointly to optimize muscle performance during prolonged contractions. The authors coined this phenomenon as muscle wisdom, opposed to the previously proposed Piper rhythm theory, since Piper rhythm was affected

by temperature, whereas motor unit firing rate behaves similarly during prolonged contractions regardless of temperature.

Linnamo et al. (55)

The purpose of this investigation was to examine the effects of pre-activation on mean spike amplitude (MSA), mean spike frequency (MSF), and force production during concentric and eccentric muscle actions. Eight men (age 21 – 30 yrs; mean body weight \pm SD = 88.6 ± 6.6 kg; height 179 ± 6.0 cm) volunteered to perform concentric and eccentric, forearm flexion muscle actions at $120^\circ \cdot s^{-1}$ with and without submaximal isometric pre-activation. Pre-activation was randomly performed at 20, 40, 60, and 80% of maximal voluntary contraction (MVC). Bipolar surface electrodes (Beckman miniaturized) were placed over the biceps brachii halfway between the motor point and the distal part of the muscle. The results of this investigation indicated a mode-specific effect for MSA and MSF. Specifically, without pre-activation MSA increased up to 80% of MVC during the concentric muscle actions, while MSA increased up to 60% of MVC during the eccentric muscle actions. With pre-activation, MSA increased equally up to 80% of MVC during the eccentric and concentric muscle actions, whereby MSA plateaued during the eccentric, but continued to increase during the concentric muscle actions. There were no significant effects for pre-activation and MSF, although MSF increased up to 60% of MVC during the eccentric muscle actions, although no change was observed during the concentric muscle actions. Regardless of mode, pre-activation increased force output compared to muscle actions started without pre-activation. MSF, however, was greater without pre-activation during the eccentric than concentric muscle

actions which indirectly suggested preferential recruitment, although this mode-specific difference diminished with pre-activation.

Westing and Seger (94)

The purpose of this investigation was to examine the velocity-related effect on the hamstring to quadriceps ratio (H/Q) and to examine the gravity effect torque (GET) on the H/Q ratio. Twenty women (mean age \pm SD = 28.2 ± 2.2 yrs; body weight 62.0 ± 6.5 kg; height 169.2 ± 5.6 cm) performed maximal, eccentric and concentric muscle actions at 60, 120, 180, 240, and $360^\circ \cdot s^{-1}$ on a calibrated isokinetic dynamometer (Spark System). In addition, subjects performed isometric muscle actions at joint angles of 40, 50, 60, and 70° for the quadriceps and 10, 20, 30, and 40° for the hamstrings. The results indicated that eccentric GET H/Q was greater than concentric GET H/Q at all test velocities. In addition, eccentric peak torque and mean torque did not change with velocity, while concentric peak torque and mean torque decreased with velocity. Without GET, the H/Q ratios were higher and this effect was further exacerbated by velocity during the concentric muscle actions, but not during the eccentric muscle actions. Isometric leg extension peak torque occurred at 50, 60, and 70° for 8, 5, and 7 of the subjects, respectively, and isometric leg flexion peak torque occurred at 10, 20, and 30° for 15, 4, and 1 subject. The authors concluded that the H/Q ratio at a given velocity may be used to predict the H/Q ratio across other velocities as reflected by the non-significant change in H/Q ratio with velocity. The H/Q ratio during the concentric muscle actions, however, could not be used to predict the H/Q ratio during the eccentric muscle actions

and vice versa. Lastly, the authors suggested using corrected GET when assessing H/Q ratios to avoid misinterpretation.

Beck et al. (7)

The purpose of this investigation was to examine the effects of submaximal and maximal concentric muscle actions on torque, electromyographic instantaneous amplitude and mean power frequency (EMG IA and EMG IMPF). Seven men (mean age \pm SD = 23.1 ± 3.4 yrs; body weight 80.5 ± 8.9 kg; height 183.6 ± 6.5 cm) and 3 women (mean age \pm SD = 19.3 ± 0.6 yrs; body weight 62.9 ± 2.9 kg; height 177.0 ± 3.9 cm) performed maximal and submaximal (20% of peak torque) concentric, forearm flexion muscle actions at $30^\circ \cdot s^{-1}$ on a calibrated Cybex II dynamometer. A bipolar surface electrode (Ag-AgCl) arrangement was placed on the biceps brachii muscle according to the recommendations of Hermens et al. (44) and Zipp (100). First and second order polynomial regression analyses were used to model the EMG IA and EMG IMPF versus force relationships. The results indicated that there were no consistent patterns for EMG IA or EMG IMPF versus force or range of motion. The authors concluded that numerous factors may have contributed to the large variability in the patterns of responses such as recording techniques (electrodes and signal processing), movement of muscle fibers and innervation zone, and the subcutaneous tissue layer that attenuates the EMG signal. The authors concluded that there is increased variability during dynamic muscle actions that contribute to the variability in the patterns of responses.

The purpose of this investigation was to examine the torque-related effects of isometric and concentric muscle actions on peak torque (PT), mean torque, electromyographic amplitude and mean power frequency (EMG AMP and EMG MPF), and mechanomyographic AMP and MPF (MMG AMP and MMG MPF) responses. Seven men (mean age \pm SD = 22.4 \pm 1.3 yrs) performed maximal and submaximal (20, 40, 60, and 80% of PT), isometric and concentric (at 30°·s⁻¹) muscle actions of the dominant leg extensors on a calibrated Cybex II dynamometer. A bipolar surface electrode (Ag-AgCl) arraignment was placed on the vastus medialis muscle according to the recommendations of Hermens et al. (44) and an accelerometer (Entran EGAS FT 10, bandwidth 0 – 200Hz) was placed between the bipolar electrode arrangement. The results indicated that EMG AMP and MMG AMP increased with force during the isometric and concentric muscle actions, and the MMG AMP values were greater near 100% of PT than at the submaximal intensities (20 – 40% of PT). For EMG MPF and MMG MPF, however, there were no significant relationships with force, except for MMG MPF which increased with force during the isometric muscle actions. The authors suggested that torque is modulated through different mechanisms during isometric versus concentric muscle actions. The lack of change in MMG MPF during the concentric muscle actions, indirectly suggested that concentric muscle actions increase force primarily through recruitment, while isometric muscle actions increase force through recruitment and firing rate.

2.4 Studies investigating the effects of isokinetic velocity on EMG and MMG responses

Evetovich et al. (32)

The purpose of this investigation was to examine the mechanomyographic (MMG) responses to maximal concentric and eccentric muscle actions across velocity and gender. Fifteen men (mean age \pm SD = 22.5 ± 1.7 yrs; body weight 79.2 ± 7.4 kg) and 16 women (mean age \pm SD = 22.8 ± 3.4 yrs; body weight 63.1 ± 9.4 kg) volunteered to perform maximal eccentric and concentric muscle actions of the dominant leg extensors at randomly ordered velocities of 30, 90, and $150^\circ \cdot s^{-1}$. All isokinetic muscle actions were performed on a calibrated Cybex 6000 dynamometer, while a piezoelectric crystal contact sensor (Hewlett-Packard 21050A) was placed over the vastus lateralis muscle. The results indicated decreases in peak torque (PT) across velocity for both males and females during the concentric muscle actions, but no change in PT across the eccentric muscle actions. Males, however, had significantly greater PT values across all velocities for both muscle actions. Furthermore, the results indicated that MMG amplitude (MMG AMP) was greater for males than females at all velocities and for both modes of muscle actions. During the concentric muscle actions, MMG AMP was greater at 90 and $150^\circ \cdot s^{-1}$ than at $30^\circ \cdot s^{-1}$ (collapsed across gender), while during the eccentric muscle actions MMG AMP was greater at $150^\circ \cdot s^{-1}$ than at 30 and $90^\circ \cdot s^{-1}$ (collapsed across gender). In addition, for males MMG AMP was greater during the concentric muscle actions than the eccentric muscle actions at $90^\circ \cdot s^{-1}$ and for the females at 30 and $90^\circ \cdot s^{-1}$. Collectively, the results indicated a velocity-specific dissociation among PT and MMG AMP, where PT decreases with velocity, but MMG AMP increased. The authors

attributed the gender-related differences in PT and MMG AMP to muscle mass and adiposity.

Ebersole et al. (29)

This study examined the velocity-related effects of repeated, maximal concentric muscle actions on torque, electromyographic amplitude and mean power frequency (EMG AMP and EMG MPF), and mechanomyographic AMP and MPF (MMG AMP and MMG MPF). Seventeen adults (mean age \pm SD = 21.8 ± 1.6 yrs; body weight 71.2 ± 11.0 kg) volunteered to perform 50 repeated, concentric, maximal muscle actions of the dominant leg extensors at randomly ordered velocities of 60 and $300^\circ \cdot s^{-1}$ on a calibrated Biodex System 3 dynamometer. Bipolar surface electrodes (Ag-AgCl) were placed over the rectus femoris (RF), vastus lateralis (VL), and vastus medialis (VM) muscles according to the recommendations of Hermens et al. (44). Accelerometers (Philips Medical Systems 21050A) were placed adjacent to the proximal border of each bipolar arrangement. The results indicated cubic decreases in torque across the 50 repeated, maximal muscle actions at 60 and $300^\circ \cdot s^{-1}$. At each velocity, the neuromuscular parameters decreased across repetitions, except EMG AMP which increased. The authors concluded that the patterns of increases or decreases were muscle- and velocity-specific which may reflect the architectural and morphological differences between muscles.

Perry-Rana et al. (73)

The purpose of this investigation was to examine velocity-related effects to repeated, maximal, concentric muscle actions on torque, and electromyographic and

mechanomyographic amplitude (EMG AMP and MMG AMP) responses. Ten adults (mean age \pm SD = 21.8 ± 2.4 yrs; body weight 62.0 ± 10.9 kg) volunteered to perform 50 repeated, maximal, concentric leg extension muscle actions at randomly ordered velocities of 60, 180, and $300^\circ \cdot \text{s}^{-1}$ on a calibrated Cybex II isokinetic dynamometer. Bipolar surface electrodes (Ag-AgCl) were placed over the vastus lateralis (VL), rectus femoris (RF), and vastus medialis (VM) muscles according to the recommendations of Ebersole et al. (28) and piezoelectric crystal contact sensors (Hewlett-Packard 21050A) were placed between each of the bipolar electrode arrangements. Collectively, the EMG responses showed no change, while torque and MMG AMP decreased across repetitions for all velocities. The authors concluded that the MMG signal may be a useful tool to demarcate fatigue. Furthermore, the patterns of responses for MMG AMP (linear, quadratic, and cubic) may reflect individual differences among muscle groups and velocity. The EMG AMP responses were best fit by cubic models for all muscles across all velocities which the authors suggested may reflect a pacing strategy employed by the subjects.

Cramer et al. (20)

The purpose of this study was to examine the effects of isokinetic velocity on peak torque (PT), mean power output (MP), electromyographic amplitude and mean power frequency (EMG AMP and EMG MPF) and mechanomyographic AMP and MPF (MMG AMP and MMG MPF). Fourteen women (mean age \pm SD = 22 ± 2 yrs) and 12 men (mean age \pm SD = 22 ± 1 yrs) volunteered to perform maximal, concentric leg extension muscle actions at 60, 120, 180, 240, 300, 360, 420, and $480^\circ \cdot \text{s}^{-1}$ on a calibrated

Cybox 6000 isokinetic dynamometer. Bipolar surface electrodes (Ag-AgCl) were placed over the rectus femoris (RF), vastus lateralis (VL), and vastus medialis (VM) muscles according to the recommendations of Cramer et al. (2000) and Cramer et al. (2001). Piezoelectric crystal contact sensors (Hewlett-Packard 21050A) were placed between each of the bipolar electrode arrangements. In general, the results indicated decreases in PT and MP across velocity, while MMG AMP and MMG MPF increased with velocity for all muscle groups. In addition, EMG AMP increased with velocity for the VL and VM, while EMG AMP decreased for the RF. For all muscles, EMG MPF decreased with velocity. These findings indicated that MMG AMP tracked the changes in MP across velocity, while MMG MPF may reflect fiber type differences between the quadricep muscles. The increase in EMG AMP with velocity, however, may be explained by an inhibitory mechanism that limits muscle activation at slow velocities acting to protect the muscle from extreme tension. Lastly, the authors warrant caution when using the neuromuscular parameters to estimate fiber-type composition, muscle architecture, and/or tissue composition due to the competing influences of cross-talk, noise, and individual differences among subjects.

Westing et al. (95)

This investigation examined the torque-velocity relationships of concentric, isometric, and eccentric muscle actions. Twenty-one resistance-trained men (mean age \pm SD = 25.3 ± 3.0 yrs; height 179.8 ± 5.6 cm; body weight 74.3 ± 5.0 kg) volunteered to perform maximal, isometric, concentric, and eccentric, leg extension muscle actions at 0, 30, 120, and $270^\circ \cdot s^{-1}$. The isometric contractions were performed at joint angles of 30,

40, 50, 60, and 70°. The results indicated that eccentric peak torque was not angle specific nor was it affected by velocity. Concentric peak torque, however, decreased with velocity and was consistently lower than isometric and eccentric peak torque, while isometric and eccentric peak torque were similar. These findings suggested that eccentric peak torque was not affected by movement velocity or joint angle. Similarly, isometric peak torque was similar across all joint angles, but was highest at 70°. The authors suggested that eccentric muscle actions may exhibit a neural mechanism which serves to protect the body and limit force production and, therefore, may explain why peak torque did not increase with velocity. Concentric peak torque, however, may be limited by motor unit recruitment, particularly at faster velocities.

Smith et al. (88)

This study examined the velocity-related effects of concentric and eccentric muscle actions on mechanomyographic and electromyographic amplitude (EMG AMP and MMG AMP). Separated by 5 minutes, 10 men (mean age \pm SD = 23 ± 2 yrs; body weight 86.7 ± 7.9 kg; height 180.6 ± 1.4 cm) performed maximal concentric and eccentric muscle actions of the dominant forearm flexors at 30, 90, and $150^\circ \cdot s^{-1}$ on a calibrated Cybex 6000 isokinetic dynamometer. A bipolar surface electrode (Ag-AgCl) and a piezoelectric crystal contact sensor (Hewlett-Packard 21050A) were placed on the biceps brachii muscle according to the recommendations of Bolton et al. (12). The results indicated no change in peak torque across velocity during the eccentric muscle actions, but peak torque decreased from 30 to $150^\circ \cdot s^{-1}$ during the concentric muscle actions. MMG AMP increased during the concentric (30 to $150^\circ \cdot s^{-1}$ and 90 to $150^\circ \cdot s^{-1}$)

and eccentric (30 to $150^{\circ}\cdot\text{s}^{-1}$) muscle actions, while there was no change in EMG AMP across velocity for either modes, although EMG AMP was greater during the concentric than eccentric muscle actions at 90 and $150^{\circ}\cdot\text{s}^{-1}$. The authors suggested that the increase in MMG AMP during the eccentric muscle actions may be due to selective recruitment of fast-twitch muscle fibers which are superficially located and result in larger oscillations. The increase in MMG AMP during the concentric muscle actions, however, was attributed to a reduction in muscle stiffness as a result of a velocity-specific effect on cross-bridge attachment which decreased with velocity. The lack of change in EMG AMP across velocity suggested that muscle activation was not affected by velocity for either mode.

2.5 Studies investigating fatigue from submaximal muscle actions

Mathiassen (60)

The purpose of this investigation was to examine the effect of work-to-rest ratio (duty cycle) and cycle time on maximal voluntary contraction (MVC), electromyographic amplitude (EMG AMP), pressure pain threshold, and blood pressure. Six sedentary women (aged $24 - 34$ yrs) volunteered to perform 7 fatiguing isometric, arm abduction muscle actions until the subjects reached endurance limit or after one hour. Bipolar electrodes were placed on the upper trapezius muscle 60% of the distance from C7 to the acromion and the second pair was placed midway between the first pair and the spinae scapulae. Measurements were taken before, after, and 4-h after each of the fatiguing trials. The results indicated increases in EMG AMP, blood pressure, and perceived fatigue throughout all fatiguing protocols. In addition, all variables were influenced by duty cycle, although only blood pressure and fatigue perception were influenced by cycle

time. It was concluded that endurance time (fatigue) was a function of mean load (which is a product of duty cycle and exercise load), while cycle time exhibited a minimal effect.

Seghers and Spaepen (82)

The purpose of this investigation was to examine the effect work-to-rest ratio and intensity during intermittent, submaximal, isometric muscle actions. Ten adults (mean age \pm SD = 21.8 ± 1.8 yrs; body weight 63.5 ± 7.8 kg) volunteered to perform 20 minutes of intermittent, isometric, forearm flexion muscle actions at 25% or 50% of maximal voluntary contraction (MVC). To create equal muscle loading, the work-to-rest ratios were manipulated during the high (5 s on, 15 s off) and low (10 s on, 10 s off) force protocols. Bipolar surface electrodes (Ag-AgCl) were placed on the biceps brachii and triceps, while a torque meter attached to the level arm measured force. The results indicated a 15% decrease in MVC torque and an increase in electromyographic root-mean-squared (EMG RMS) for both protocols. EMG median frequency (EMG MDF), however, remained unchanged for the high force protocol, but EMG MDF decreased during the low force protocol. In addition, during the low force protocol the triceps were less active when compared to the high force protocol. The authors postulated that the potential fatigue-related effects on EMG MDF may be counterbalanced by additional motor unit recruitment (as suggested by the increase in EMG RMS) which resulted in no change in EMG MDF during the high force protocol. During the low force protocol, a slow but progressive decrease in EMG MDF may reflect the drop-out of fatigued motor units despite increases in muscle activation.

This investigation examined the effects of simulated motorcycle riding on electromyographic root-mean-squared (EMG RMS) and EMG mean frequency responses (EMG MF). Twenty motorcycle riders (mean age \pm SD = 28.4 ± 7.5 yrs; body weight 73.1 ± 7.4 kg) 39 control (mean age \pm SD = 25.3 ± 3.8 yrs; body weight 71.4 ± 5.7 kg) subjects volunteered to perform intermittent and continuous isometric hand grip muscle actions. Bipolar surface electrodes (Ambu blue sensors) were placed on flexor carpi radialis and flexor digitorum superficialis muscle according to the recommendations of the SENIAM project (44). The results indicated that the riders were able to perform more intermittent rounds than the control group, but no difference was observed in the continuous protocol. Normalized EMG RMS was greater during the continuous protocol than the intermittent protocol for both groups and increased throughout each round. Normalized EMG MF, however, decreased across rounds during the continuous protocol, while EMG MF decreased for the flexor carpi radialis across the second to third round and for the flexor digitorum superficialis across the third to fourth round during the intermittent muscle actions. Furthermore, for the flexor carpi radialis there was a significant three-way interaction between group, round, and muscle. EMG RMS of the flexor carpi radialis was greater in the riders than the control group during the continuous protocol. The authors concluded that the intermittent protocol was able to differentiate riders from non-riders, while the neuromuscular responses were less sensitive to this dissociation. The authors suggested that rest periods be limited to a minute or less during intermittent isometric muscle actions to prevent recovery which may explain the lack of

change in the neuromuscular parameters between the motorcycle riders and the control group.

2.6 Studies investigating fatigue from maximal muscle actions

Camic et al. (18)

The purpose of this investigation was to examine the effects of repeated, maximal isometric and concentric muscle actions on torque, electromyographic amplitude and mean power frequency (EMG AMP and EMG MPF) and mechanomyographic AMP and MPF (MMG AMP and MMG MPF) responses. Twelve resistance-trained women (mean age \pm SD = 21.1 ± 1.4 yrs; body weight 63.3 ± 7.4 kg) volunteered to perform 30 repeated, maximal isometric and concentric muscle actions of the dominant leg extensors on a calibrated Cybex 6000 dynamometer. A bipolar surface electrode (Ag-AgCl) arrangement was placed on the vastus medialis muscle according to the recommendations of Hermens et al. (44) and an accelerometer (Entran EGAS FT 10, bandwidth 0 – 200Hz) was placed between the bipolar electrode arrangement. The results indicated decreases (linear $r^2 = 0.95$ and quadratic $R^2 = 0.97$) in torque during the concentric and isometric muscle actions, respectively. In addition, during the isometric muscle actions there were decreases in EMG AMP (quadratic, $R^2 = 0.44$), EMG MPF (linear, $r^2 = 0.62$), and MMG MPF (linear, $r^2 = 0.48$), but no change in MMG AMP. For the concentric muscle actions, there were decreases in EMG AMP (quadratic, $R^2 = 0.46$), EMG MPF (quadratic, $R^2 = 0.86$), MMG AMP (quadratic, $R^2 = 0.44$), and MMG MPF (quadratic, $R^2 = 0.80$). The authors concluded that the decreases in torque and the associated neuromuscular parameters during the isometric and concentric muscle actions were related to increased

intramuscular pressure and the occlusion of blood flow which led to the accumulation of metabolic byproducts and may have adversely affected excitation-contraction coupling.

Kay et al. (47)

The purpose of this study was to examine the effects of maximal, isometric, concentric, and eccentric muscle actions on maximal voluntary contraction (MVC), integrated electromyographic (iEMG), and EMG mean power frequency spectrum (EMG MPFS). Twelve subjects (mean age \pm SD = 25.1 \pm 3.7 yrs; body weight 70.1 \pm 8.2 kg) volunteered to perform 55 repeated, maximal, concentric (CON) and eccentric (ECC) leg extension muscle actions at 60°·s⁻¹ and a sustained, maximal, isometric (ISO) contraction for 100-s. All testing was performed using a Kin-Com dynamometer and the EMG signals were detected using triode electrodes (Thought Technology Triode MIEP01-00) placed over the rectus femoris muscle. There were decreases in torque during the ISO and CON protocols, while there was no change in torque during the ECC protocol. During the ISO protocol, iEMG decreased and was lower than iEMG of the CON and ECC protocols which exhibited no change. For all protocols, EMG MPFS decreased and the decrease was greater during the ISO and CON protocols. The authors concluded that the decreases observed during the ISO protocol may be related to decreased neural drive and ischemia from increased intramuscular pressure, while the decreases observed during the CON protocol cannot be explained by the same fatigue-related mechanisms. The lack of change during the ECC protocol may be the result of an inability to fully activate skeletal muscle and, thus, delay muscle fatigue. In addition, the authors suggested that the EMG MPFS was less affected during the ECC protocol possibly due to increased

intramuscular temperature which offset the fatigue-related effects on action potential conduction velocity.

Gray and Chandler (43)

The purpose of this study was to examine the effects of repeated, maximal concentric and eccentric muscle actions on torque. Sixteen women (aged 22 – 32yrs) volunteered to perform 40 repeated, maximal, concentric and eccentric, leg extension muscle actions at $180^{\circ}\cdot s^{-1}$ on a calibrated Kin-Com dynamometer. To examine the fatigue-related effects on torque, percent decline was calculated from the mean of the first and last five repetitions. The results indicated decreases in concentric peak torque (PT), but no change in eccentric PT. Therefore, the authors suggested eccentric muscle actions were more robust to the fatigue-induced effects of repeated, maximal muscle actions. The authors attributed the dissociations between the concentric and eccentric muscle actions to the greater metabolic demand associated with concentric muscle actions and increased mechanical efficiency during the eccentric muscle actions. The authors recommended further research to examine the effects of velocity on strength adaptations during concentric and eccentric training, and to examine the series elastic components as a potential mechanism to delay muscle fatigue.

Tesch et al. (92)

The purpose of this study was to examine the effects of repeated, maximal concentric and eccentric muscle actions on torque and integrated electromyographic (iEMG) and EMG mean and median power frequency (EMG MPF and EMG MDPF). Fourteen men (mean age \pm SE = 33 ± 2 yrs; body weight 81 ± 3 kg) volunteered to

perform 3 bouts of 32 repeated, maximal concentric and eccentric muscle actions of the dominant leg extensors at $180^{\circ}\cdot\text{s}^{-1}$ on a calibrated Kin-Com isokinetic dynamometer. Bipolar surface electrodes (Ag-AgCl) were placed over the vastus lateralis (VL) and rectus femoris (RF) muscles. The repetitions were plotted as the average of every 3 repetitions after omitting the first and last repetition of every bout. The results indicated significant decreases in torque across the concentric muscle actions, but no changes in eccentric torque production. iEMG was greater for the concentric versus eccentric muscle actions and iEMG/torque increased during the concentric muscle actions, but remained unchanged during the eccentric muscle actions. For the VL, iEMG remained unchanged for both concentric and eccentric muscle actions, while for the RF, iEMG decreased during the concentric muscle actions. Furthermore, EMG MPF and EMG MDPF decreased for the VL and RF across concentric muscle actions, but remained unchanged across the eccentric muscle actions. The authors attributed the lack of change in torque, iEMG, iEMG/ torque, EMG MPF, and EMG MDPF during the repeated eccentric muscle actions as a function of greater mechanical efficiency. In addition, the eccentric muscle actions may have benefited from decreased muscle activation which allowed for a greater rotation of the activated motor units and delayed the onset of muscle fatigue.

Westing et al. (96)

This investigation examined the differences between voluntary and electrically evoked torque during concentric, eccentric, and isometric muscle actions. Nine men (mean age \pm SEM = 30 ± 2.2 yrs; body weight 78 ± 1.9 kg; height 183 ± 1.6 cm)

performed maximal voluntary, superimposed, and electrically evoked isometric, concentric, and eccentric, leg extension muscle actions at 60, 180, and $360^{\circ}\cdot\text{s}^{-1}$ on a Spark System dynamometer. Electrical stimulation was applied percutaneously using a Medelec NS6 electrical stimulator (Medelec, Surrey, UK) until the subjects could no longer tolerate any additional increase in voltage. The results of the present study indicated that superimposed twitch and electrically evoked torque was greater (21 – 24% and 11 – 12%) than voluntary torque under eccentric conditions for all velocities. Furthermore, superimposed and electrically evoked eccentric torques were greater (20 – 23% and 25 – 31%) than superimposed and electrically evoked isometric and concentric torque. For concentric torque, superimposed torque was greater than voluntary torque at $180^{\circ}\cdot\text{s}^{-1}$, but was similar at 60 and $360^{\circ}\cdot\text{s}^{-1}$, although concentric torque was less than isometric torque. For isometric torque, superimposed torque and voluntary torque were similar, while electrically evoked was 10% less than voluntary torque. The present findings indicated that under voluntary conditions both isometric and concentric muscle actions could be maximally activated. Eccentric muscle actions, however, may be limited by the Golgi Tendon Organ that acts to inhibit force production. Under all conditions, however, eccentric torque was greater than concentric and isometric torque. Ebersole et al. (29)

This study investigated the mechanomyographic and electromyographic amplitude and mean power frequency (EMG AMP, EMG MPF, MMG AMP, and MMG MPF) responses to fatiguing, maximal, concentric muscle actions. Seventeen adults (mean age \pm SD = 21.8 ± 1.6 yrs; body weight 71.2 ± 11.0 kg; height 171.6 ± 7.8 cm) performed 50 repeated, maximal concentric muscle actions of the leg extensors at 60 and

$300^{\circ}\cdot\text{s}^{-1}$ on a calibrated Biodex 3 isokinetic dynamometer. Bipolar surface electrodes (Ag-AgCl) were placed over the rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM) muscles according to the recommendations of Hermens et al. (44) and piezoelectric crystal contact sensors (Hewlett-Packard 21050A) were placed between each of the bipolar electrode arrangements using double-sided adhesive tape. The polynomial regressions indicated cubic decreases for torque at both 60 and $300^{\circ}\cdot\text{s}^{-1}$. For the neuromuscular responses, EMG AMP and MMG AMP were best fit by cubic models, while EMG MPF decreased uniquely for each muscle and there were no consistent responses for MMG MPF. The authors attributed the decline in torque to the drop-out of more fatigable type II muscle fibers which may also explain the periods of decreases in EMG AMP during the fatiguing bout. The cubic relationships for EMG AMP across all three muscles may reflect a potential pacing strategy where the subjects exerted less effort during the middle of the test to save energy for the remaining repetitions. The muscle-specific decreases in EMG MPF may be due to architectural differences (longer muscles tend to have slower conduction velocities) or morphologically, where the decrease in EMG MPF was related to the dropout of type II muscle fibers which have faster conduction velocities. Like EMG AMP, the MMG AMP responses were best fit by cubic models, except for the VM at $60^{\circ}\cdot\text{s}^{-1}$ which increased linearly and may be due to several competing factors such as intramuscular pressure, muscle fusion, and/or morphological differences. The MMG MPF responses, however, varied for muscle groups across velocity which may reflect morphological differences and/or muscle wisdom.

Beck et al. (9)

This study investigated the mechanomyographic and electromyographic amplitude and mean power frequency (EMG AMP, EMG MPF, MMG AMP, and MMG MPF) responses to fatiguing, maximal, concentric muscle actions. Seven men (mean age \pm SD = 23 ± 3 yrs; body) and 3 women (mean age \pm SD = 20 ± 2 yrs; body) performed 50 repeated, maximal, concentric muscle actions of the forearm flexors at $180^\circ \cdot s^{-1}$ on a calibrated Cybex II isokinetic dynamometer. A bipolar surface electrode (Ag-AgCl) arrangement was placed over the biceps brachii (BB) muscle according to the recommendations of Orizio et al. (1992) and Smith et al. (1998) and a piezoelectric crystal contact sensor (Hewlett-Packard 21050A) was placed using double-sided adhesive tape according to the recommendations of Ebersole et al. (2002) and Smith et al. (1998). The results indicated decreases in torque, MMG AMP, MMG MPF, and EMG MPF, but increases in EMG AMP. The authors suggested that the decreases in MMG AMP and MMG MPF may be related to a dropout of fatigued motor units, the effects of muscle wisdom, and/or a reduction in muscle compliance. The increases in EMG AMP may reflect increased effort exerted by the subjects towards the end of the fatiguing protocol and/or due to peripheral fatigue that may have led to contraction failure. The decreases in EMG MPF, however, cannot be entirely explained by decreases in action potential conduction velocity and, therefore, the authors suggested further research be done to analyze the relationship between action potential conduction velocity and fatiguing, dynamic muscle actions.

Chapter III

METHODS

3.1 Subjects

Twelve men (mean age \pm SD = 22.6 ± 2.2 yrs; body weight = 84.0 ± 8.3 kg; height = 178.6 ± 8.3 cm) volunteered to participate in this investigation. The subjects regularly participated in resistance training (8.1 ± 2.2 hours per week) and had no known cardiovascular, pulmonary, metabolic, muscular, and/or coronary heart disease, or regularly used prescription medication. The subjects visited the laboratory on 2 occasions separated by at least 48-h and were instructed not to perform upper body exercise 48-h prior to each visit. The study was approved by the University Institutional Review Board for Human Subjects and all subjects completed a health history questionnaire and signed a written informed consent prior to testing.

3.2 Procedures

Familiarization (Visit 1). The first laboratory visit consisted of an orientation session to familiarize the subjects with the testing protocols. During the orientation, the subjects performed submaximal and maximal concentric $60^\circ \cdot s^{-1}$ and isometric muscle actions of the forearm flexors. The subjects visually tracked torque production using real-time torque displayed on a computer monitor programmed using LabVIEW 13.0 software (National Instruments, Austin, TX) and practiced performing concentric muscle actions at 65% of concentric peak torque (PT).

Determination of Concentric PT and Isometric MVC. During visit 2, the subjects performed a warm-up consisting of 10 – 15 submaximal (approximately 50 – 75% of

concentric PT), concentric muscle actions of the dominant (based on throwing preference) forearm flexors at $60^{\circ} \cdot s^{-1}$ on a calibrated Cybex II dynamometer. After 2-min of rest, the subjects randomly performed 5 concentric PT and 5 isometric MVC trials (13). The concentric muscle actions were performed at $60^{\circ} \cdot s^{-1}$ through a full range of motion and the isometric muscle actions were performed for 4-s at an elbow joint angle of 115° (68, 69). The highest concentric and isometric torque from each of the 5 trials (excluding the first trial, (13)) was selected as the pretest concentric PT and pretest isometric MVC, respectively.

Determination of Submaximal, Concentric Muscle Actions. Following the determination of the pretest concentric PT and pretest isometric MVC, the subjects performed 50 submaximal (65% of their pretest concentric PT), concentric muscle actions at $60^{\circ} \cdot s^{-1}$. Real-time torque was displayed on a computer monitor. In addition, a light bulb indicated the start and end of each repetition which was displayed on the same computer monitor as the real-time torque. For analyses, only subjects that maintained 65% ($\pm 5\%$) of concentric PT across all 50 submaximal, concentric muscle actions were used. After completing the 50 submaximal, concentric muscle actions, the subjects randomly performed 5 posttest concentric PT and 5 posttest isometric MVC trials using the same procedures as the pretest (13).

Electrode and Accelerometer Placements. During visit 2, a bipolar (30 mm center-to-center) surface EMG electrode (circular 4 mm diameter silver/silver chloride, BIOPAC Systems, Inc., Santa Barbara, CA) arrangement was placed on the dominate arm over the biceps brachii muscle according to the recommendations of Barbero et al.

(3). The reference electrode was placed over the acromion process. Prior to each electrode placement, the skin was shaved, carefully abraded, and cleaned with alcohol. The MMG signal from the biceps brachii was detected using an accelerometer (Entran EGAS FT 10, bandwidth 0 – 200 Hz, dimensions: 1.0 x 1.0 x 0.5 cm, mass: 1.0 g, sensitivity: 651.6 mV/g) that was placed between the proximal and distal EMG electrodes of the bipolar arrangement using double-sided adhesive tape.

Signal Processing. The raw EMG and MMG signals were digitized at 1000 Hz with a 12-bit analog-to-digital converter (Model MP100, Biopac Systems, Inc.) and stored in a personal computer (ATIV Book 9 Intel Core i7 Samsung Inc., Dallas, TX) for subsequent analyses. The EMG signals were amplified (gain: x 1000) using differential amplifiers (EMG 100, Biopac Systems, Inc., Santa Barbara, CA, bandwidth = 10 – 500 Hz). The EMG and MMG signals were digitally bandpass filtered (fourth-order Butterworth, zero-phase shift) at 10 – 500 Hz and 5 – 100 Hz, respectively. All signal processing was performed using custom programs written with the LabVIEW programming software. The EMG (μV root-mean-square, μV_{rms}) and MMG ($\text{m}\cdot\text{s}^{-2}$) amplitude (AMP) and mean power frequency (MPF) (Hz) values for the concentric and isometric muscle actions were calculated for the middle third of each contraction. Thus, during the concentric and isometric muscle actions signal epochs of 0.50-s and 1.33-s were used, respectively, to calculate the AMP and MPF values of the EMG and MMG signals. These portions of the signals were selected to avoid the acceleration and deceleration phases that are typical of isokinetic dynamometers (14) and to avoid the initial gross lateral movement of the muscle at the onset of muscle contraction (65). In addition, the EMG and MMG values from the 50 submaximal, concentric muscle actions

were averaged across 10 time points where each time point was the average of every 5 repetitions (i.e. time point 1 = mean of repetitions 1-5, time point 2 = 6-10, and so on). For the MPF analyses, each data segment was processed with a Hamming window and the Discrete Fourier transform (DFT) algorithm (27, 52). The MPF was selected to represent the power spectrum in accordance with the recommendations of Hermens et al. (44).

3.3 Statistical Analyses

Paired t-tests were used to examine pretest versus posttest concentric PT and isometric MVC torque values as well as EMG AMP, EMG MPF, MMG AMP, and MMG MPF values assessed during the concentric PT and isometric MVC muscle actions. In addition, a paired t-test was used to examine the percent decreases for concentric PT versus isometric MVC torque. The 10 time points across the 50 submaximal, concentric muscle actions were normalized to the first time point (i.e. repetitions 1-5) and polynomial regression analyses (first, second, and third order) were used to examine the composite patterns of responses for EMG AMP, EMG MPF, MMG AMP, and MMG MPF across the 50 submaximal, concentric muscle actions. The F-test was used to determine if the increment in proportion of variance accounted for by a higher-order polynomial was significant (72). All statistical analyses were performed using IBM SPSS v. 21 (Armonk, NY) and an alpha of $P \leq 0.05$ considered statistically significant for all comparisons.

Chapter IV

RESULTS

4.1 Concentric PT and Isometric MVC Torque and Neuromuscular Responses

Tables 1 and 2 provide the means and standard deviations for the torque and the associated neuromuscular parameters during the concentric PT and isometric MVC muscle actions, respectively. As a result of the fatiguing workout there were significant decreases in concentric PT (23.3%) and isometric MVC (17.0%) from pretest to posttest, but the percent decreases were not different between modes (Figures 1 and 2). During the concentric PT muscle actions, there was a significant mean decrease from pretest to posttest for EMG MPF (11.8%), while EMG AMP, MMG AMP, and MMG MPF remained unchanged (Figure 1). During the isometric MVC muscle actions, however, there were no significant mean changes from pretest to posttest for EMG AMP, EMG MPF, MMG AMP, or MMG MPF (Figure 2).

4.2 Neuromuscular Responses across the 50 Submaximal, Concentric Muscle Actions

Figure 3 shows the composite results of the polynomial regression analyses for EMG AMP, EMG MPF, MMG AMP, and MMG MPF across the fatiguing workout. In addition, Table 3 displays the absolute values across the 10 time points for EMG AMP, EMG MPF, MMG AMP, and MMG MPF. The analyses for the composite data indicated a linear increase in EMG AMP ($r^2 = 0.961$), a quadratic decrease in EMG MPF ($R^2 =$

0.771), and linear decreases in MMG AMP ($r^2 = 0.747$) and MMG MPF ($r^2 = 0.575$)

across the 50 submaximal, concentric muscle actions.

Chapter V

DISCUSSION

5.1 Pretest versus Posttest Measures of Concentric PT and Isometric MVC Torque

The results of the present study indicated that there was no mode-specific effect for percent decline in maximal torque following the submaximal fatiguing workout. That is, even though the fatiguing workout involved concentric, isokinetic muscle actions, there was no difference in the percent declines in concentric PT (23.3%) and isometric MVC (17.8%). These findings were consistent with those of Camic (16) who reported a 20.3% decline in concentric PT and a 16.5% decline in isometric MVC following 30 maximal, concentric, isokinetic, leg extension muscle actions. Thus, the results of the present study, in conjunction with those of Camic (16), indicated that fatigue-induced decreases in concentric PT and isometric MVC were manifested similarly following both submaximal and maximal, fatiguing, concentric workouts.

5.2 Pretest versus Posttest Neuromuscular Responses During the Concentric PT and Isometric MVC Muscle Actions

In the present study, the neuromuscular parameters did not track the fatigue-induced pretest to posttest decreases in concentric PT or isometric MVC. Specifically, as a result of the fatiguing workout EMG AMP, MMG AMP, and MMG MPF remained unchanged when assessed during the pretest versus posttest concentric PT and isometric MVC muscle actions. During the concentric PT muscle actions, however, EMG MPF decreased, but remained unchanged during the isometric MVC muscle actions. These findings were in partial agreement with those of Camic (16) who reported no change in

EMG AMP or MMG AMP, but decreases in EMG MPF and MMG MPF during both the concentric PT and isometric MVC muscle actions following 30 maximal, concentric, leg extension muscle actions. The decreases in MMG MPF reported by Camic (16), but not in the present study, may have been the result of the use of repeated, maximal muscle actions versus submaximal muscle actions at 65% of concentric PT. Perhaps the greater intensity of the fatiguing muscle actions of Camic (16) caused a decrease in the firing rates of the activated motor units and MMG MPF that did not occur under the submaximal conditions of the present study. It is also possible, however, that the fatigue-related patterns of MMG MPF responses were affected by differences between the present study and that of Camic (16) with regard to the characteristic of the muscles involved. In the present study, the neuromuscular responses were measured from the biceps brachii which is characterized by a fusiform architecture, while Camic (16) measured from the vastus lateralis which is a unipennate muscle. Muscle architecture related factors such as muscle geometry, origin, and length may also influence the neuromuscular responses to fatiguing workouts (15, 46). It remains unclear, however, why EMG AMP, MMG AMP, and MMG MPF were unaffected by the fatiguing workout, but EMG MPF decreased only when measured during the concentric PT muscle actions. The current findings indicated a fatigue-related effect for EMG MPF responses when measured during concentric PT muscle actions that was not evident during the isometric MVC muscle actions. The mechanism underlying this mode-specific neuromuscular response is unclear.

5.3 Time-Course of Neuromuscular Responses During the Fatiguing, Submaximal Workout

The results of the present study indicated that for the composite data, EMG AMP increased linearly ($r^2 = 0.961$), while EMG MPF decreased quadratically ($R^2 = 0.771$), and MMG AMP and MMG MPF decreased linearly ($r^2 = 0.747$ and $r^2 = 0.575$, respectively) across the 50 fatiguing, submaximal, concentric, isokinetic muscle actions. These patterns of responses were partially consistent with those (9, 18, 73) during maximal, concentric muscle actions. For example, across 50 maximal, concentric ($180^\circ \cdot s^{-1}$), forearm flexion muscle actions Beck et al. (9) reported increases in EMG AMP (cubic, $R^2 = 0.707$), but decreases in EMG MPF (quadratic, $R^2 = 0.939$), MMG AMP (linear, $r^2 = 0.774$), and MMG MPF (linear, $r^2 = 0.939$). The patterns of responses for EMG AMP of Beck et al. (9), however, were best fit with cubic models which were attributed to both physiological and psychological factors (9). For example, Beck et al. (9) suggested that the plateau in EMG AMP during the middle phase of the test (repetitions 20 – 40) may have reflected a pacing strategy and/or decreased motivation. The increase in EMG AMP during the beginning of the fatiguing task, however, may have been a function of non-maximal effort and pacing during the early phase of the test, while the increase in EMG AMP at the end of the fatiguing task may have been a function of increased effort, but impaired muscle contractility. Furthermore, it has been hypothesized (9) that the decreases in MMG AMP and MMG MPF may have been a function of the dropout of fatigable fast-twitch motor units, decreased muscle compliance, and/or the effects of muscle wisdom. The decreases in EMG MPF may have reflected a fatigue-induced slowing of action potential conduction velocity (9).

In the present study, the linear increase in EMG AMP across repetitions likely reflected either the fatigue-induced recruitment of motor units or synchronization, but not increasing motor unit firing rates (since MMG MPF decreased). The recruitment of additional motor units becomes necessary to replace those that, because of excitation contraction coupling failure, can no longer contribute to force production (18, 66, 81). This fatigue-related motor unit activation strategy has been attributed to the buildup of metabolic byproducts such as lactate, inorganic phosphate, and ammonia which interfere with contractile properties of the activated muscle fibers (30, 35, 56, 57, 93). Although there is some disagreement (40, 78), the effect of lactate and inorganic phosphate accumulation on force production may be due to the effects of calcium release and reuptake by the sarcoplasmic reticulum, actin-myosin binding affinity, troponin-calcium binding affinity, ATP breakdown via ATPase, and ATP production in the metabolic pathways (93). In addition, ammonia accumulation during exercise can adversely affect action potential propagation (56, 57). Thus, it is possible that the fatigue-induced buildup of metabolic byproducts caused excitation-contraction coupling failure and led to the increase in motor unit recruitment to maintain the submaximal workout. It has also been suggested (25, 97), however, that EMG AMP may increase due to the effects of motor unit synchronization. Motor unit synchronization results in an efficient and synchronous activation of motor units to optimize force production (5, 26, 49, 64, 84, 97). Recently, however, Kline and De Luca (50) have questioned the validity of motor unit synchronization as a true activation strategy and have referred to it as an “epiphenomenon” (p. 178). For example, in their recent simulation study, Kline and De Luca (50) found that motor unit synchronization decreased with the progression of

fatigue and with increased force production. Thus, in the present study it is likely that the increase in EMG AMP was due to motor unit recruitment and not synchronization.

It has been suggested (8, 68, 69) that under some conditions, MMG AMP reflects motor unit recruitment. In the present study, however, MMG AMP remained unchanged. During a fatiguing task MMG AMP tends to increase at low intensities (10 – 40% of isometric MVC), but remains unchanged or decreases at higher intensities (50 – 100% of isometric MVC) (41, 70, 79). In the present study, it is possible that decreased muscle compliance had a greater influence on MMG AMP than did the increase in motor unit recruitment which may explain the increase in motor unit recruitment, but the decrease in MMG AMP. For example, an increase in intramuscular fluid pressure from repeated and prolonged muscle actions may decrease muscle compliance (87) and restrict the lateral oscillations of the activated muscle fibers, thereby, decreasing MMG AMP (9).

The decrease in MMG MPF in the present study may have been due to the increase in motor unit recruitment and/or to the effects of muscle wisdom. For example, De Luca and Contessa (23) and Kline and De Luca (50) reported that later recruited high-threshold motor units were characterized by lower firing rates than earlier recruited low-threshold motor units which had higher firing rates. This inverse hierarchical of motor unit firing rates has been referred to as the “Onion-Skin Scheme” (23, 24). Therefore, in the present study it is possible that the decrease in MMG MPF was a function of motor unit recruitment. Specifically, as fatigue developed higher-threshold motor units with lower firing rates were recruited to maintain force output. It is also possible, however, that the decrease in MMG MPF could be attributed to the effects of the Muscle Wisdom Theory

including decreased muscle relaxation times and motor neuron discharge rates, as well as a greater fusion of motor unit twitches to optimize force production (36-39, 59).

Collectively, in the present study the decrease in MMG MPF may have reflected the recruitment of higher-threshold motor units and/or was related to the effects of muscle wisdom which optimized force production during the fatiguing workout.

In summary, the results of the present study indicated that there was no mode-specific effect for percent decline in concentric PT or isometric MVC following the submaximal fatiguing workout. As a result of the fatiguing workout, EMG AMP, MMG AMP, and MMG MPF remained unchanged when assessed during the pretest versus posttest concentric PT and isometric MVC muscle actions. During the concentric PT muscle actions, however, EMG MPF decreased, but remained unchanged during the isometric MVC muscle actions. It remains unclear, however, why EMG AMP, MMG AMP, and MMG MPF were unaffected by the fatiguing workout, but EMG MPF decreased only when measured during the concentric PT muscle actions. Across the 50 fatiguing, submaximal, concentric, isokinetic muscle actions EMG AMP increased, while EMG MPF, MMG AMP, and MMG MPF decreased. The increase in EMG AMP, but decreases in EMG MPF and MMG MPF may have reflected the fatigue-induced recruitment of higher-threshold motor units with lower firing rates (as described by the Onion-Skin Scheme) due to the buildup of metabolic byproducts which interfere with contractile properties of the activated muscle fibers. Despite potential increases in motor unit recruitment, MMG AMP decreased which may have been due to decreased muscle compliance that had a greater influence on MMG AMP than did the increase in motor unit recruitment. In addition to the Onion-Skin Scheme, it is also possible that the

decrease in MMG MPF could be described by the Muscle Wisdom Theory which optimizes force production. Collectively, in the present study the increase in EMG AMP and decrease in MMG MPF may have reflected an increase in motor unit recruitment, but a decrease in motor unit firing rate which suggested that the maintenance in torque could be explained by both the Onion-Skin Scheme as well as the Muscle Wisdom Theory.

Table 1. Pretest versus posttest means \pm SD during the concentric peak torque (PT) muscle actions.

	Pretest	Posttest
Concentric PT (Nm)*	84.0 \pm 18.3	64.4 \pm 13.3
EMG AMP (μ Vrms)	1397.8 \pm 639.3	1337.0 \pm 455.3
EMG MPF (Hz)*	73.5 \pm 12.1	64.8 \pm 10.9
MMG AMP ($\text{m}\cdot\text{s}^{-2}$)	0.67 \pm 0.19	0.78 \pm 0.15
MMG MPF (Hz)	39.7 \pm 8.3	27.9 \pm 8.3

*Significant at $P \leq 0.05$ for pretest $>$ posttest

Note: Electromyographic (EMG) amplitude (AMP), EMG mean power frequency (MPF), mechanomyographic (MMG) AMP, and MMG MPF.

Table 2. Pretest versus posttest means \pm SD during the isometric maximal voluntary contraction (MVC) muscle actions.

	Pretest	Posttest
Isometric MVC (Nm)*	98.6 \pm 20.8	81.1 \pm 15.0
EMG AMP (μ Vrms)	1404.9 \pm 841.7	1280.1 \pm 516.6
EMG MPF (Hz)	71.8 \pm 11.9	71.6 \pm 13.9
MMG AMP ($\text{m}\cdot\text{s}^{-2}$)	0.58 \pm 0.15	0.63 \pm 0.16
MMG MPF (Hz)	25.5 \pm 7.2	23.4 \pm 4.6

*Significant at $P \leq 0.05$ for pretest $>$ posttest

Note: Electromyographic (EMG) amplitude (AMP), EMG mean power frequency (MPF), mechanomyographic (MMG) AMP, and MMG MPF.

Table 3.

Composite means \pm SD for the 10 time points across the 50 submaximal, concentric muscle actions for electromyographic (EMG) amplitude (AMP), EMG mean power frequency (MPF), mechanomyographic (MMG) AMP, and MMG MPF from the biceps brachii.

Time Point	EMG AMP (μ Vrms)	EMG MPF (Hz)	MMG AMP ($\text{m}\cdot\text{s}^{-2}$)	MMG MPF (Hz)
1	1054.5 \pm 203.5	65.9 \pm 5.7	0.76 \pm 0.12	34.0 \pm 5.1
2	1075.1 \pm 182.4	66.2 \pm 4.7	0.77 \pm 0.11	31.9 \pm 4.5
3	1099.8 \pm 153.4	65.7 \pm 4.5	0.74 \pm 0.10	32.3 \pm 4.2
4	1180.2 \pm 148.8	66.1 \pm 4.9	0.71 \pm 0.10	32.9 \pm 4.9
5	1196.2 \pm 162.2	64.7 \pm 4.5	0.67 \pm 0.09	30.0 \pm 4.4
6	1222.4 \pm 129.5	66.9 \pm 4.6	0.68 \pm 0.11	30.9 \pm 4.6
7	1240.0 \pm 118.5	64.3 \pm 5.0	0.67 \pm 0.11	31.5 \pm 5.6
8	1261.3 \pm 142.0	64.6 \pm 4.7	0.64 \pm 0.08	31.0 \pm 4.6
9	1334.7 \pm 134.2	62.7 \pm 3.8	0.67 \pm 0.09	29.7 \pm 4.4
10	1339.7 \pm 168.3	62.8 \pm 4.1	0.64 \pm 0.10	30.6 \pm 6.2

Each time point is the mean of 5 repetitions (i.e. time point 1 = mean of repetitions 1-5; time point 2 = mean of repetitions 6-10; and so on).

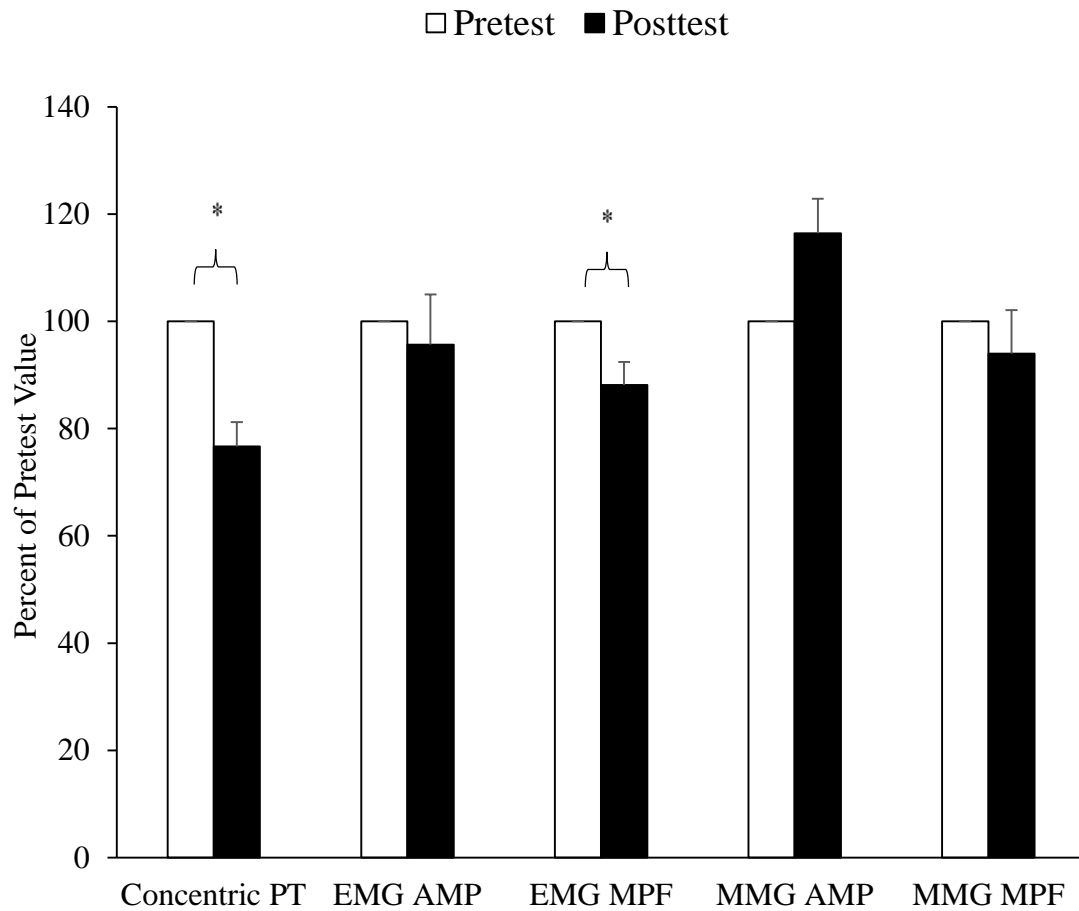


Figure 1.

Pretest and posttest means (\pm standard error) for concentric peak torque (PT), electromyographic (EMG) amplitude (AMP), EMG mean power frequency (MPF), mechanomyographic (MMG) AMP, and MMG MPF during the concentric PT muscle actions.

* Significant ($P \leq 0.05$) decrease from pretest to posttest.

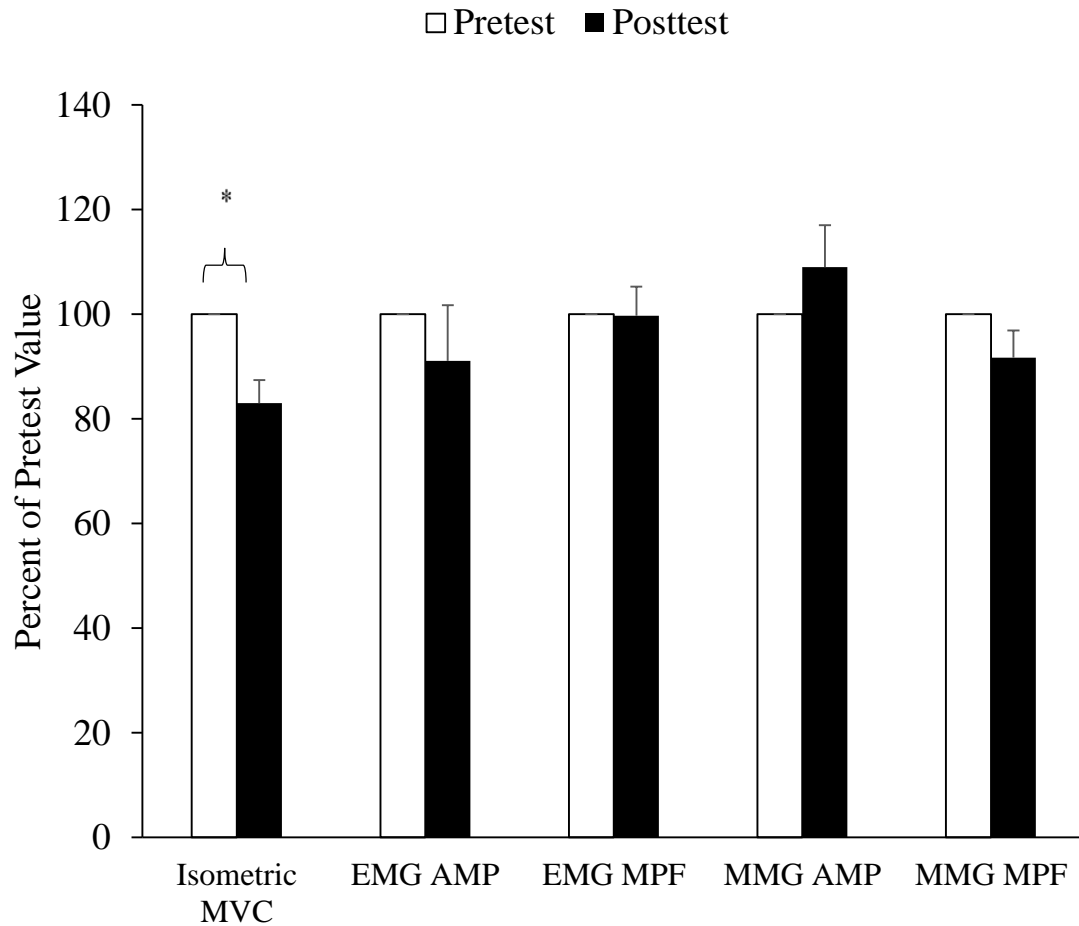


Figure 2.

Pretest and posttest means (\pm standard error) for isometric maximal voluntary contraction (MVC) torque, electromyographic (EMG) amplitude (AMP), EMG mean power frequency (MPF), mechanomyographic (MMG) AMP, and MMG during the isometric MVC muscle actions.

* Significant ($P \leq 0.05$) decrease from pretest to posttest.

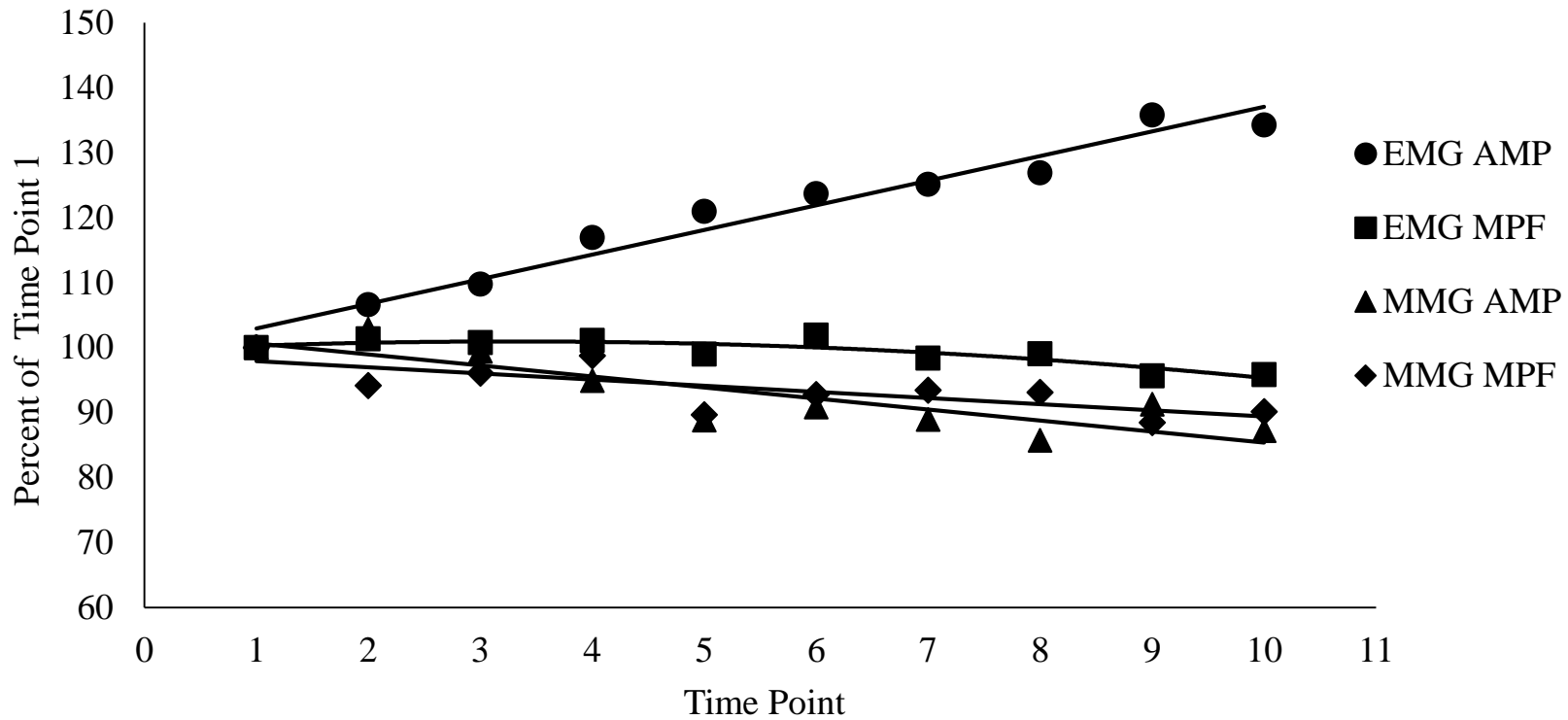


Figure 3. The composite results of the polynomial regression analyses for the 10 time points for electromyographic (EMG) amplitude (AMP), EMG mean power frequency (MPF), mechanomyographic (MMG) AMP, and MMG MPF from the biceps brachii across the 50 submaximal, concentric muscle actions. Each time point is the average of 5 repetitions (i.e. time point 1 = mean of repetitions 1-5; time point 2 = mean of repetitions 6-10; and so on).

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APPENDIX A

Glossary

Concentric PT – Concentric peak torque

Isometric MVC – Isometric maximal voluntary contraction

EMG – Electromyography

MMG – Mechanomyography

AMP – Amplitude (μV_{rms} or $\text{m}\cdot\text{s}^{-2}$)

MPF – Mean power frequency (Hz)

Nm – Newton-meters

SE – Standard error

SD – Standard deviation

APPENDIX B

Human Performance Laboratory
Center for Youth Fitness and Sports Research
Department of Nutrition and Health Sciences
110 Ruth Leverton Hall
University of Nebraska-Lincoln
Lincoln, NE 68583-0806



IRB# 20150315046EP
Date Approved: 03/03/2015
Valid Until: 03/03/2016

Director: Terry J. Housh, Ph.D.

Statement of Informed Consent**Title of Research Study**

Electromyographic and mechanomyographic, time and frequency responses during fatiguing, submaximal, isokinetic muscle actions of the biceps brachii.

Invitation to Participate

You are invited to participate in this research study. The following is provided in order to help you make an informed decision whether or not to participate. If you have any questions, please do not hesitate to ask.

Basis for Subject Selection

You were selected as a potential participant because you either identify as a male or female between the ages of 19 and 29 years, in good health, and are moderately trained. Moderately trained will be defined as participating in resistance training exercise 3 to 5 days per week for at least 30 to 60 minutes for the last six months. If you wish to participate you must fill out a health history questionnaire. You will be prevented from participating in this research study if there are indications from the questionnaire that you may have health risks. Such indications include symptoms suggestive of chest pain, breathing difficulties, irregular heartbeat, kidney or liver problems, high blood pressure or cholesterol, and/or abnormal electrocardiogram (EKG). Muscle or skeletal disorders including previous or current finger, hand, wrist, and/or elbow injuries may also preclude you from participation in this study. If you have no muscle/skeletal disorders or disease that will prevent you from engaging in physical activity, you will be asked to perform the tests described below. Overall, there are numerous health-related issues that may preclude you from participation in this study and inclusion will be determined on a subject-by-subject basis. Furthermore, you must be willing to forgo exercise 24 hours prior to testing, forgo any

performance or fitness related supplementation throughout the testing duration, and forgo any weight loss or diet programs throughout the testing duration.

Purpose of the Study

The primary purpose of this study is to examine the neuromuscular responses associated with repeated, submaximal, concentric, forearm flexion muscle actions. Essentially, this study is examining the electrical and mechanical activity in your arm during the lifting (shortening) phase of a bicep curl.

Explanation of Procedures

You will be asked to visit the Human Performance and Body Composition Laboratories located in Mabel Lee Hall (Room 141& 151) on 2 separate days, separated by 24 – 48 hours. On each day you will complete forearm flexion (bicep curl) muscle actions on an isokinetic dynamometer. Each visit will range from 30 to 60 minutes in duration.

Collection of Measurements:

Muscle electrical activity will be measured using soft foam surface electrodes that stick to the skin over your arm muscles (biceps brachii and brachioradialis). Muscle mechanical activity will be recorded with an accelerometer attached with double-sided tape to the surface of the skin between each of the electrode configurations over your arm muscles. Placement of the electrodes involves careful skin abrasion of the 2 electrode sites. Following careful skin abrasion, 2 pairs of electrodes will be placed on your biceps brachii and brachioradialis muscles of your dominant arm. Another electrode will be placed on your shoulder, the medial acromion specifically. In addition, 2 MMG sensors (accelerometers) will be placed on your arm with double-sided adhesive tape between each of the electrode pairs.

Screening & Experimental Visit 1:

The first laboratory visit will consist of an orientation to familiarize you with the testing protocols. Following correct positioning on the Cybex II isokinetic dynamometer, you will be asked to perform a warm-up consisting of 10 concentric isometric muscle actions of your dominant forearm flexors (based on throwing preference) corresponding to approximately 50% of your maximum effort. A concentric muscle action is a movement by which the muscle contracts or shortens under tension, while an isometric muscle action is a static contraction where no actual movement of the limb occurs despite providing force. A 30-second rest period will be provided between each warm-up contraction. Following the warm-up, you will practice maximal

concentric and isometric muscle actions of the forearm flexors. During the maximal muscle actions, you will be encouraged to try as hard as you can to pull your arm towards your body. You will then practice a series of submaximal, concentric muscle actions corresponding to 65% of your maximum effort. You will be provided with feedback regarding your torque production after each contraction. All concentric muscle actions in this study will be performed at a medium speed (velocity of $60^{\circ}\cdot\text{s}^{-1}$) and will be performed through a full range of motion.

Experimental Visit 2:

Following the placement of the electrodes and the accelerometers as described in the “Collection of Measurements” section, you will be positioned the same and perform the same warm-up contractions that were performed during Visit 1. After this, you will be asked to perform the concentric testing protocol. The protocol will consist of randomly performing 5 maximal concentric and 5 maximal isometric forearm flexion muscle actions. Following the maximal muscle actions, you will perform 50 submaximal, concentric, forearm flexion muscle actions at 65% of your maximal concentric peak torque. Immediately after completing the 50 submaximal, concentric, forearm flexion muscle actions, you will be asked to perform 5 more maximal concentric and 5 more maximal isometric forearm flexion muscle actions. Like visit 1, all concentric muscle actions will be performed at a medium speed (velocity of $60^{\circ}\cdot\text{s}^{-1}$) and will be performed through a full range of motion.

Total Time Commitment

The total time commitment for the 2 visits in this study will be approximately 90 minutes. The first visit will take approximately 30 minutes, while visit 2 will take approximately 60 minutes. The 2 visits will be completed within a 2-week period, with at least 24 hours between the first and second visit.

Potential Risks and Discomforts

The following are the potential risks and discomforts you may experience during this study:

- Electrode Preparation and Use – The use of electrodes and the preparation of the skin for their application may lead to the remote possibility of complications such as a rash or infection.
- Strength Tests – Performing maximal strength tests may lead to muscle tears or soreness, dizziness, headache, acute elevation of blood pressure, heart attack, stroke, or sudden death.

Protection Against Risks

To minimize any potential risks and/or discomforts, you will be given instructions for special stretches, which may aid in the elimination of any muscle soreness as a result of the tests. In

addition, you will be asked repeatedly during the tests how you feel in relation to your ability to continue the test. Throughout all the tests, you will be monitored by laboratory personnel trained in Cardiopulmonary Pulmonary Resuscitation (CPR) and use of an Automated External Defibrillator (AED). In addition, you will be asked repeatedly if you feel you can continue the tests. An anti-bacterial salve will also be applied to the abraded skin area to reduce the risk of infection.

Potential Benefits to Subjects

The main benefit from participating in this study will be feedback in regards to your level of muscular strength and endurance of your forearm flexors. Additional information will be provided such as: the amount you fatigue (strength loss) after performing the exercise protocol and what that may mean in terms of your muscle fiber type distribution in your forearm flexors.

In Case of Emergency Contact Procedures

If you are injured while you are in Mabel Lee Hall during your participation in the study, inform one of the investigators who will contact the University Health Center. If you experience an injury as a direct result of the study, but are not in personal contact with an investigator, please contact the University Health Center or your local health care provider. You may always contact any of the investigators listed at the end of this consent form if you have any questions.

Medical Care in Case of Injury

In the unlikely event that you should suffer an injury as a direct consequence of the research procedures described above, the acute medical care required to treat the injury can be provided at the University of Nebraska Health Center from the hours of 8:00 a.m. – 6:00 p.m. Monday through Thursday, 8:00 a.m. – 5:00 p.m. Friday, and 9:00 a.m. – 12:30 p.m. Saturday. If the University Health Center is unable to treat you, emergency care is available at local community health providers. All medical expenses will be the responsibility of the participant.

Assurance of Confidentiality & Release of Medical Records

Any information obtained from this study, which could identify you, will be kept strictly confidential and any research-related medical records that were collected during the study may be sent to the University of Nebraska-Lincoln Institutional Review Board. The information may be published in scientific journals or presented at scientific meetings, but your identity will be kept strictly confidential. All data collected as a result of your participation will be kept in a locked cabinet in the office of the primary investigator (Room 141 Mabel Lee Hall). Your data will be coded and there will be a list linking your name to the code. This list will be destroyed within 1 year of the end of data collection. Your data will be compiled and only group data will be used for dissemination without identifying your name. For the purposes of future reference, your data will be stored for a minimum of 15 years. In the chance of a medically related injury, you will be

asked to sign a Private Health Information Authorization release form from the appropriate medical provider to allow access to any related medical records to ensure proper review of the medical-related injury.

Rights of Research Subjects

You may ask any questions concerning this research and have those questions answered before agreeing to participate in or during the study. Or you may call the investigator, Ethan Hill, at any time, office phone, (402) 472-2690, or after hours (262) 215-4636. You may also contact Dr. Terry Housh at his office phone, (402) 472-1160, or after hours (402) 416-5734. Please contact the investigator:

- if you want to voice concerns or complaints about the research
- in the event of a research related injury. Please contact the University of Nebraska-Lincoln Institutional Review Board at (402) 472-6965 for the following reasons:
- you wish to talk to someone other than the research staff to obtain answers to questions about your rights as a research participant
- to voice concerns or complaints about the research
- to provide input concerning the research process
- in the event the study staff could not be reached.

Voluntary Participation Withdrawal

You are free to decide not to participate in this study, or to withdraw at any time without adversely affecting your relationship with the investigators or the University of Nebraska. Your decision will not result in any loss of benefits to which you are otherwise entitled

Termination From the Study

The investigators have the right to drop you from the study if it is for your own protection or if you are noncompliant with the study protocol. For example, if you are unable to perform the physical protocol requirements necessary for completion of the exercise test, you will be dropped from the study. In addition, you have the right to voluntarily withdraw from the study at any time.

Voluntary Participation

You are voluntarily making a decision whether or not to participate in this research study. Your signature certifies that the content and meaning of the information on this consent form have been fully explained to you and that you have decided to participate having read and understood the information presented. Your signature also certifies that you have had all your questions answered to your satisfaction. If you think of any questions during this study, please contact the investigators. You will be given a copy of this consent form to keep.

Signature of Research Participant

Date

Printed name of Research Participant

My signature as witness certifies that the subject signed this consent form in my presence as his/her voluntary act and deed.

Signature of Independent Third Party

Date

Investigators:

Ethan Hill

work phone (402) 472-2690

home phone (262) 215-4636

Terry Housh

work phone (402) 472-1160

home phone (402) 416-5734

PRE-EXERCISE TESTING HEALTH STATUS QUESTIONNAIRE

Participant ID _____ Date _____

Home Address _____

Work Phone _____ Home Phone _____

E-mail address _____

Person to contact in case of emergency _____

Emergency Contact Phone _____ Your Birthday (mm/dd/yy) ____/____/____

Personal Physician _____ Physician's Phone _____

Gender _____ Age _____ (yrs) *Height ____ (ft) ____ (in) *Weight ____ (lbs)

*Blood Pressure _____ *we will take these measures today

Does the above weight indicate: a gain ____ a loss ____ no change ____ in the past year?

If a change, how many pounds? _____ (lbs)

A JOINT-MUSCLE STATUS (✓Check areas where you currently have problems)

Joint Areas

- ☐ Wrists
☐ Elbows
☐ Shoulders
☐ Upper Spine & Neck
☐ Lower Spine
☐ Hips
☐ Knees
☐ Ankles
☐ Feet
☐ Other _____

Muscle Areas

- ☐ Arms
☐ Shoulders
☐ Chest
☐ Upper Back & Neck
☐ Abdominal Regions
☐ Lower Back
☐ Buttocks
☐ Thighs
☐ Lower Leg
☐ Feet
☐ Other _____

B HEALTH STATUS (✓Check if you previously had or currently have any of the following conditions)

- | | |
|--|--|
| <input type="checkbox"/> High Blood Pressure | <input type="checkbox"/> Acute Infection |
| <input type="checkbox"/> Heart Disease or Dysfunction | <input type="checkbox"/> Diabetes or Blood Sugar Level Abnormality |
| <input type="checkbox"/> Peripheral Circulatory Disorder | <input type="checkbox"/> Anemia |
| <input type="checkbox"/> Lung Disease or Dysfunction | <input type="checkbox"/> Hernias |
| <input type="checkbox"/> Arthritis or Gout | <input type="checkbox"/> Thyroid Dysfunction |
| <input type="checkbox"/> Edema | <input type="checkbox"/> Pancreas Dysfunction |
| <input type="checkbox"/> Epilepsy | <input type="checkbox"/> Liver Dysfunction |
| <input type="checkbox"/> Multiple Sclerosis | <input type="checkbox"/> Kidney Dysfunction |
| <input type="checkbox"/> High Blood Cholesterol or Triglyceride Levels | <input type="checkbox"/> Phenylketonuria (PKU) |
| <input type="checkbox"/> Loss of Consciousness | <input type="checkbox"/> Allergic Reactions to Medication |
| <input type="checkbox"/> Others That You Feel We Should Know About _____ | please describe _____ |
| <input type="checkbox"/> Pregnant | <input type="checkbox"/> Allergic Reactions to Any Other Substance |
| | please describe _____ |

C. PHYSICAL EXAMINATION HISTORY

Approximate date of your last physical examination _____

Physical problems noted at that time _____

Has a physician ever made any recommendations relative to limiting your level of physical exertion? _____ YES _____ NO

If YES, what limitations were recommended? _____

Have you ever had an abnormal resting electrocardiogram (ECG)? _____ YES _____ NO

D. CURRENT MEDICATION USAGE (List the drug name and the condition being managed)

<u>MEDICATION</u>	<u>CONDITION</u>
_____	_____
_____	_____
_____	_____

E. PHYSICAL PERCEPTIONS (Indicate any unusual sensations or perceptions. ! Check if you have recently experienced any of the following during or soon after *physical activity* (PA); or during *sedentary periods* (SED))

<u>PA</u>	<u>SED</u>	<u>PA</u>	<u>SED</u>
<input type="checkbox"/>	<input type="checkbox"/> Chest Pain	<input type="checkbox"/>	<input type="checkbox"/> Nausea
<input type="checkbox"/>	<input type="checkbox"/> Heart Palpitations "fast irregular heart beats"	<input type="checkbox"/>	<input type="checkbox"/> Light Headedness
<input type="checkbox"/>	<input type="checkbox"/> Unusually Rapid Breathing	<input type="checkbox"/>	<input type="checkbox"/> Loss of Consciousness
<input type="checkbox"/>	<input type="checkbox"/> Overheating	<input type="checkbox"/>	<input type="checkbox"/> Loss of Balance
<input type="checkbox"/>	<input type="checkbox"/> Muscle Cramping	<input type="checkbox"/>	<input type="checkbox"/> Loss of Coordination
<input type="checkbox"/>	<input type="checkbox"/> Muscle Pain	<input type="checkbox"/>	<input type="checkbox"/> Extreme Weakness
<input type="checkbox"/>	<input type="checkbox"/> Joint Pain	<input type="checkbox"/>	<input type="checkbox"/> Numbness <input type="checkbox"/>
Other _____		<input type="checkbox"/>	<input type="checkbox"/> Mental Confusion

F. FAMILY HISTORY (✓Check if any of your blood relatives . . . parents, brothers, sisters, aunts, uncles, and/or grandparents . . . have or had any of the following)

- ☐ Heart Disease
☐ Heart Attacks or Strokes (prior to age 50)
☐ Elevated Blood Cholesterol or Triglyceride Levels
☐ High Blood Pressure
☐ Diabetes
☐ Sudden Death (other than accidental)

G. CURRENT HABITS (✓Check any of the following if they are characteristic of you current habits)

- ☐ Smoking. If so, how many per day?
 - ☐ Regularly does manual garden or yard work
 - ☐ Frequently walks for exercise
 - ☐ Frequently rides a bicycle
 - ☐ Frequently runs for exercise
 - ☐ Regularly participates in a weight training exercise program
 - ☐ Engages in a sports program more than once per week.
- If so, what does the program consist of?

How many hours of aerobic training (running, biking, swimming, walking, elliptical, etc) do you participate in per week?

J. Have you taken any nutritional supplements (i.e., vitamins, protein supplements, creatine, amino acids, etc.) within the last six weeks? (YES NO) If so, please list the type of supplement you are taking, the dosage used, and how long you have been taking it.

Supplement	Dosage	Length of Time Taking It

K. Medication Use (Put a check mark next to any medications that you are currently taking on a regular basis or have taken on a regular basis in the last 6 months.)

Prescription Medications:

- ☐ Xenical (orlistat)
- ☐ Meridia (sibutramine hydrochloride monohydrate)
- ☐ Adipex (phentermine)
- ☐ Ionamin (phentermine resin)
- ☐ Bontril (phendimetrazine tartrate)
- ☐ Antidepressants such as Welbutrin, Paxil and Prozac
- ☐ Systemic sympathomimetic-containing products
- ☐ Coumadin or Warfarin
- ☐ MAOIs
- ☐ Tricyclics
- ☐ Lithium

Over the Counter Medications and Supplements containing:

- ☐ Creatine or creatine-containing products
- ☐ Protein-based supplements
- ☐ Amino Acid containing supplements
- ☐ Aspirin except for cardiac prophylaxis at 81mg/day
- ☐ Ephedra or pseudoephedrine
- ☐ Ma Huang
- ☐ Guarana
- ☐ Chromium picolinate (unless part of a multi-vitamin)
- ☐ Green Tea Leaf (unless part of a multi-vitamin)
- ☐ Heartleaf Extract
- ☐ Vanadium (unless part of a multi-vitamin)
- ☐ Bitter Orange (Citrus aurantium)
- ☐ Phaseolamin (white bean extract or carb blocker)
- ☐ Chitosan (fat blocker)
- ☐ Fenfluramine
- ☐ Phenylpropanolamine
- ☐ Niacin